NASA TECHNICAL TRANSLATION NASA TT F-15,906

TERRESTRIAL APPLICATIONS OF THE PHOTOVOLTAIC SOLAR GENERATORS

Centre National d'Etudes Spatiales

Translation of: "Les applications terrestres des générateurs solaires photovoltaiques" Centre National d'études spatiales, Paris, France, Report, 1974, pp 1-78

(NASA-TT-F-15906) TERRESTRIAL APPLICATIONS OF THE PHOTOVOLTAIC SOLAR GENERATORS (Scientific Translation Service) CSCL 10A

N74-31536

Unclas
G3/03 47760

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 SEPTEMBER 1974

STANDARD TITLE PAGE

1. Report No. NASA TT F-15,906	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle TERRESTRIAL APPLICATIONS OF THE PHOTOVOLTAIC SOLAR GENERATORS		5. Report Date September 1974
		6. Performing Organization Code
7. Author(s) National Center for Space Research		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address SCITRAN Box 5456 Santa Barbara, CA 93108		11. Contract or Grant No. NASw-2483
		13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Les applications terrestres des générateurs solaires photovoltaiques", Centre National d'études spatiales, Paris, France, Report, 1974, pp 1-78

16. Abstract

The future prospects of solar generators are discussed. An analysis is made of the present state throughout the earth of the application of photovoltaic energy. The future prospects in France and other countries are discussed, followed by three supplements covering hydrogen storage of electric power produced by solar cells and the climatology of solar radiation.

PRICES SUBJECT TO CHANGE

17. Key Words (Selected by Author(s))	18. Distribution Statement Unclassified - Unlimited

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

SUMMARY

The fact that the industrial use of photovoltaic energy on Earth is very important today was the starting point for the CNES to analyze the future prospects of this field. The interest of such a study has become more obvious with increasing concern in problems of energy and pollution for most countries.

The first thing to analyze was the state of progress in the field of solar cells. Then the reasons for the relatively high production cost in the actual stage of technology were examined. A technical orientation which would allow a progressive decrease of the production costs was then put forth.

On the other hand, the first study of the economics involved was started in particular to indicate the possibilities for photocells on the market as a function of the change in the cost forecast. This study, which will be followed in more detail, shows that the future market is far from negligible.

It is difficult to estimate at this point the marketing importance that this operation can reach. At best, one can remark that it is a function of the evolution of the manufacturing cost, and that, in this area, the prospects are very good.

TABLE OF CONTENTS

I. INTRODUCTION

In this report we have voluntarily omitted general considerations concerning the total energy situation, and the problems introduced by pollution. It seems useful, however, to give a few general thoughts on the questions frequently asked about the domestic uses of solar energy. /3*

1. <u>Solar energy is very rarefied, and the area of land necessary to install the solar generators is prohibitive</u>.

   In full sun, a panel of 1 m^2 can give, depending on the technique in use, between 100 and 160 W. A square of the size 80 × 80 km would be sufficient to cover the present electricity needs of the United States. This corresponds to a minimal surface of the available deserts of the U.S.A.

   For comparative purposes, one should remark that a hydroelectric power station occupies a surface ten times greater than a photovoltaic generator of the same horsepower. Moreover, the solar power stations probably would not have the same power per unit as a classical electric power plant. Solar energy being already distributed, this fact could be exploited to install the solar generators at the place of

*Numbers in the margin indicate pagination in the original foreign text.

utilization, and to adapt their size to the particular need (transmitting stations, housing, supermarket, factory, power station for railways).

Let us note that a panel of about 150 m^2 in the United States, and of $35m^2$ in France, would be sufficient to cover all the needs of a household of four, all year long.

2. The number of hours of insolation might be sufficient in Africa, but would be too short in Europe.

Depending upon the areas, the difference in hours of sunlight between Africa and France varies, on the average, by a factor of 2. In France, the maximum duration of insolation is 2,800 hours in Provence. The minimum is about 1600 hours in the regions of the North. As an average, one can plan on about 2000 hours. In Africa, however, the maximum of 4000 hours is reached in the "solar belts"; these are the deserts and semi-desert areas of the North and South. In Central Africa, the amount of sun is considerably decreased by excessive humidity. In the southern states of the United /4
States, the insolation can reach 4000 hours.

For comparison purposes, an EDF (Electricity de France) power station works an average of 5000 hours per year. However, the heat generation station can reach 8000 hours. Therefore, many power stations function for a number of hours equal to the total duration of yearly sunshine.

3. A good part of the consumption of electricity occurs at hours "with no sun".

There is then a problem of storage. Utilization of nuclear energy presents a similar problem. The nuclear power plants are apparently difficult to regulate according to the needs. Extensive efforts are made in the United States to solve the problem of storage (in part, with the help of electrochemical cells) because of the prospects offered by nuclear reactors.

4. The reliability of solar generators still must be proved.

The percentage of power failures in solar generators, installed on satellites or on the Earth, seems to be quite negligible. Some of those reactors have operated since 1960. This reliability has been acquired since the experimental stage, and will have to be confirmed by multiple large scale experiments.

Regarding the reliability, the nuclear reactors are also worrisome: one-third of the nuclear power plants in the United States are now inactive for technical reasons.

5. The time necessary to "amortize" energy output, the energy invested in manufacturing a solar panel, is prohibitive.

The only remark on this subject was made by Professor Wolf of the University of Pennsylvania: (the "Si" type) would have to function for six months on Earth before the energy used during the manufacture of the reactor itself could be recovered. At the actual state of industrial production, which is non-optimal from the energy point of view, the delay for this recovery could reach dozens of years.

This analysis is easily done for the solar generators. Is it for the hydroelectric and nuclear reactors?

At a conference in Palo Alto, an engineer from Westinghouse /5
gave the figure of 10 years as the necessary time of use of a nuclear reactor to recover the energy invested. Without doubt, it seems that 1973 in the U.S.A. was the first year to give a positive energy balance in the area of nuclear power plants.

6. <u>The solar cells are too expensive</u>.

It is true, but the past efforts directed toward this problem were minimal because of the technical restraints due to space use. The prospects for a significant decrease of the costs are excellent.

II. WORLDWIDE STATE OF THE APPLICATION ON EARTH OF PHOTOVOLTAIC ENERGY

II.1. Techniques, existing and planned operations

A photovoltaic solar generator is composed of 4 sub-systems: /6

- the "solar panel" itself, formed by the association of a number of elementary photovoltaic cells.

- a means of storing electrical energy, usually built in a "buffer" in order to compensate for the variation in solar energy, either for short periods (clouds, night/day) or for longer periods (seasonal variations).

- a regulation electronics;

- a mechanical support for the solar panel, which can be either fixed (optimum middle range orientation to collect maximum energy), or movable (it can, as a limit, be "subjected" to the direction of the solar rays).

The design and the integration of the complete system are usually accomplished by a "prime manufacturer" alone.

In the space applications, this leadership is usually provided by the aerospace industry, and not by a manufacturer of reactors.

In terrestrial applications, this leadership is provided by a manufacturer of cells. This sounds logical, to the extent that the cost of the "solar panel" represents 80 to 90% of the cost of the complete system. But, if an important effort toward the technology of cells were to change this balance, this assignment of leadership would not be necessarily optimal from the point of view of total cost.

We attempted to make a list of manufacturers of solar generators for terrestrial applications (Table 1). This list is certainly not complete since this area of industrial operation changes very rapidly.

Before going into an analysis of the state of progress of the technology, one can give some elements of qualitative appreciation on the actual market for solar reactors. /8

The spatial applications represent a very fluctuating market, but which can be estimated to be about 100 kW per year (1% in France).

The spatial applications are certainly far below this level now, but they probably will give rise to a much more important market in a few years (cf. II.3.). A number of stations have been placed in different areas of the world, and are all, to our knowledge, in the experimental stage. We can mention the following realizations:

— SHARP, Japan: 730 operations in 14 countries (cf. documentation in Supplement 4): Japan, Korea, Taiwan, Singapore, Malaysia, Indonesia, Australia, Canada, Pakistan, Saudi Arabia, Kuwait, South Africa. These operations sustain:

- some marine warning buoys (ports, offshore, signals on high seas), lighthouses, beacons, railway signals. Devices for security in mountains (landslides...). Apparatus to measure fog, apparatus for meteorological measurements, clocks, transistorized receivers.

TABLE 1.

Manufacturer	Country	State of Progress	Technology
SPECTROLAB	U.S.A.	Sells	Si
SOLAREX	U.S.A.	Sells	Si
SOLAR POWER CORP. (EXXON)	U.S.A.	Sells	Si
SOLAR ENERGY SYSTEMS Inc. (SHELL, DU PONT)	U.S.A.	Do not Sell Yet	CdS
WESTING-HOUSE	U.S.A.	Do not Sell Yet	CdS
R T C	France	Sells	Si
S A T	France	Planning Stage	Si and CdS
I R D	G.B.	Sells	Manufactures CdS, Interested by Si
B A C (?)	G.B.	Do not sell	Si
SHARP ELECTRONICS	Japan	Sells	Si
"ACADEMY of SCIENCE"	U.S.S.R.	Sells	Si

— U.S.S.R.: The total photovoltaic power in the Soviet union is in the range 5 kW. Three generators of 1 kW each are installed in Turkmenia, Armenia and near the Black Sea on gazeoducs. Insolation in measurements for meteorology are also performed with the help of photocells. (However, in Western countries, thermoreactors are used).

— R T C, France: In 12 years, installations of 4 - 5 kW have /9 been built in 6 countries: France, England, Nigeria, Saudi Arabia, Chile, Peru. They operate airport beacons (radio and light), harbor buoys, school televisions, re-transmitters, copper refining.

— SPECTROLAB and SOLAREX: They are at present the most important manufacturer of terrestrial equipment on the market. We do not have the characteristics of their market.

— NASA, JPL: In the United States, NASA is most interested in the applications of solar energy. In addition to the interest for heating and cooling houses by solar energy (construction of "solar buildings" in Langley, Marshall Center, etc.), NASA's high competence in the area of photovoltaic generators points toward an important activity in this field.

NASA-LEWIS installed, 2 years ago, a test-panel on a building of their Center. They also operate, now for one year, a meteorological station functioning on solar reactors.

JPL in Pasadena has been experimenting since 1968 with solar reactors built from available spare parts for spacecraft. Reactors from SPECTROLAB, CENTRALAB and SHARP were used.

There have been designed, built and tested power sources for seismic observatories (California, for AEC in Nevada, in Mexico), a portable radio-transmitter, 2 buoys in San Diego harbor, a radio-beacon on the California Coast, telemetery, telphone apparatus, alarm systems on large military camps, etc.

In the detailed analysis of the state of technological progress, /10
we will limit our study to the reactors (basic component of "solar panel"), and to the means of storage.

The electronics of regulation consist of very simple techniques well known to many companies. As for the mechanical support, it is a matter either of very simple techniques, in the case of fixed support, or of very sophisticated (but well-mastered) techniques for pivoting controlled devices. In the latter case, it is still not proved that systems sufficiently economical can be devised to compete with the former.

II.1.1. Techniques of cells

II.1.1.1. Silicon cells

II.1.1.1. a. Manufacturing cells

The manufacturing process begins always with circular cells, 200 - 300 μ thick. The cost of the disks used as raw material to make "1 W" varies from $3 to $7.

The technology of the junction is the same one as developed in the past for space applications, doping by phosphorus to obtain the N layer on the side exposed to the the sun.

As far as space applications are concerned, no effort was made towards industrialization: the market was too small, too irregular, and the specifications required by each group of researchers were different, so that no mass production could be considered. A few years ago, one of the two large American manufacturers had to stop production for a whole year. In Europe, where space research is even less important, and where the market for the military — which is decisive in the U.S.A. — is virtually absent, the situation is even worse: the manufacturing process can be really called "handicrafts".

A much better situation is expected on the terrestrial /11
market, since the orders will be more substantial and regular and, also, can be satisfied only by mass produced components. For this newly discovered market, however, great efforts toward industrialization have to be made.

The American company Solarex has recently improved their manufacturing process so that it is more simple than the previous one. This process produces reactors with a yield of 20 to 40% greater, so that even without large scale production, reactors of the type Si at $10 a watt can be turned out (reactors not assembled).

Another advantage of this process seems to be its flexibility: one can easily change one specification for another. This is an important factor in the beginning, when the orders must be taken as they come.

The geometry of terrestrial reactors is different from space reactors. In order to use as well as possible the available surface of the satellites, the solar reactors for space are always built by coupling rectangular cells. But the plates of silicon used for manufacturing reactors are always discoidal to start with, since the methods of production of monocrystalline silicon only permit pulling out cylindrical bars which are then cut off in small disks.

For terrestrial applications, in order to maximally simplify the manufacturing process and to minimize raw material losses, discoidal cells are used which are then cut in halves or quarters of disks, so that:

- RTC uses full disks; /12
- Sharp uses half-disks;
- Solarex uses quarter-disks.

III.1.1. b. Assembling silicon reactors

For space applications, the Si-type reactors are connected by metallic wires (Ag, silver Moly...). To put together two cells in series, a wire is soldered on the front face of the first cell (negative contact), then brought back and soldered onto the rear face of the second one (positive contact). Tin or electrical solder is used.

Another technique, called "wrap around", produces reactors where the negative contact is brought to the rear face <u>within the semi-conductor</u>. This makes the process more complicated, but simplifies assembly. Effectively, all the cells of a module can be put on a printed circuit and (by heating, for example) welded together in one operation.

A priori, it seems that the "wrap around" technique is more interesting for large scale production than for a small manufacturing process. It is significant to note that in space projects, Americans use this process of fabrication for manufacturing large generators, but it is not yet used in Europe.

Also, the company with the greatest worldwide experience for terrestrial applications, Sharp, Japan, offers its module standard with "wrap around" cells.

II.1.1.1. c. Protection of silicon modules

For space applications, each cell is covered by gluing on a glass plate with a non-reflecting layer. The non-reflecting layer increases notably the power output of the reactor (20 to 30%), but is relatively expensive. Economically, it might be possible to eliminate this layer /13 on terrestrial applications, the resulting loss of power being compensated for by the use of high performance reactors.

This seems to be the case for Solarex, which produces bare slab modules with an efficiency of 15% (AM1).

RTC does not use anti-reflecting layers, and claims an efficiency in the range (AM1) of 10%.

Sharp uses the anti-reflection layers and gives an efficiency "greater than 10% (AM1)".

However, the panels have to be protected against rain, sand, mud, etc.

Glass plates are used by the Soviet Union. The results obtained in desert areas (Turkmenia) seem to be disappointing.

RTC also uses highly resistant hardened glass, and assert that they obtain good results.

Sharp and Solarex use resins (acrylic resins) and also obtain excellent results.

In Cleveland, NASA is experimenting with plexiglass with very satisfactory results.

It seems, then, that the necessary materials are available on the market, but that long experience is needed on the specific needs of terrestrial reactors.

II.1.1.2. CdS cells

It is now a well known fact that the only worldwide manufacturer of stable CdS solar cells is the SAT in France. /14

To our knowledge, the various American companies who have started research in this area have not yet been successful in building a satisfactory CdS model.

For terrestrial applications, where lifetime is a decisive factor, the technology of CdS is hindered because stability can be acquired only at the price of very strict controls and specifications.

On the other hand, the CdS solar panels must be sealed in a neutral atmosphere. (For the solar panels Si, however, the USSR guarantees a lifetime of 10 to 15 years; and in the United States, a figure greater than 20 years is accepted. It is well known that the components of the Si type can possibly fail at the contact level, but never at the junction level.)

SAT can produce, safely and regularly, CdS cells of high performance, and stable enough to be considered for the terrestrial market. In 1973, for instance, SAT has been able to produce, in a small pilot manufacturing experiment about 30 reactors of large surface (27 cm^2) with an efficiency in the range of 6.5%, and with a stability checked by accelerated testing.

II.1.1.3. Ga As generators

Cells with thin layers of gallium arsenide were studied in the 60's by Americans. The junction is formed by a deposition of a thin layer of Cu_2 Se. These studies were /15 never conclusive.

The utilization of Ga As monocrystals is considered too expensive in Western countries. In the USSR, however, some Ga As solar generators were used (monocrystalline cells, apparently) three years ago on the lunar vehicle. The Russians admit that this technique is expensive, but assert that the Ga As cells were the only ones able to resist the important thermal cycling observed on the lunar surface (+ 200° C to - 200° C).

II.1.1.4. Cd Te generators

In the 60's, GE in the U.S.A. and RTC in France developed some cells with thin layers of Cd Te by a technique of precipitation in vapor phase. GE gave up the research in 1968. RTC estimated that the price of a solar generator with Cd Te would be rapidly inferior to the prices of the Si type generator now manufactured.

RTC attempted commercialization with cameras. The CNES has observed a deterioration of these cells, and has discontinued its financial support in favor of the CdS line.

TRC gave up this line around 1970, the market at this time being insufficient.

II.1.2. Techniques of storage

Among the available solutions of industrial storage, the one which stands out most is the method using lead batteries, because of its cost. The most important problem is reliability. It is desirable for the different subcomponents forming a photovoltaic solar generator to have comparable reliability.

The manufacturers of cells can at present guarantee a /16
reliability of 10 to 20 years.

Though the manufacturers are optimistic in forecasts of the lifetime of lead batteries' built-in "buffers" (functioning in favorable conditions), it seems that we still lack "long term" experience in this area. We certainly have better data concerning the reliability of other currently used techniques for space applications: Ni-Cd, Ag-Cd, Zn-Ag. But these techniques do not seem to be competitive at the price level.

II.2. Prospects of technical developments and effect on costs

II.2.1. Solar cells

II.2.1.1. Si-type cells

The process by which plates of monocrystalline Si are pre- /17
pared for use in building cells can be considered as highly industrialized today. It is not by a simple effort of industrialization that it will be possible to lower the limit of $3 per watt. To reach this objective, more basic research, costly, but necessary, will have to be reactivated.

The price of the raw material represents an important part of the total cost of the cell, so that the first objective is the use of silicon slices as thin as possible. The price of $3 per watt is equivalent to a mass of silicon about 600 μ thick (300 μ for the plate and 300 μ lost in sawing). The output of the cell does not really depend on the thickness, as long as this is greater or equal to about 10 μ.

The first objective should then consist of finding a way to pass from 600 to 10 μ of thickness. The mass used will decrease by as much, and also the price, only if the technique of plate preparation is completely changed. At this time, the process is as follows: the temperature of the polycrystalline silicon is raised to the melting point; from this molten silicon bath, monocrystalline bars are drawn out about 1 meter long and from 2 - 10 cm in diameter, varying with the requirement of the order. These bars are then sawn. During this phase, the consumption of silicon corresponds to the use of 600 μ slices, half for sawing and half for the plates ready for treatment. It is impossible to saw plates less than 600 μ thick: no thinner saws exist, and below 250 μ, the plates become more and more fragile.

To obtain thinner plates, a number of techniques can be considered; all require the use of a support to ensure the mechanical rigidity of the thin slab of silicon (10 μ, for instance). The silicon manufacturing methods which /18
appear to be promising are, among others:

— deposit of silicon on a substrate in vapor phase;
— pulling of monocrystalline sheets replacing the drawing of cylindrical bars;
— drawing of thick sheets with rolling and gluing on a support.

All these methods eliminate the operation of sawing, and lead directly to thin sheets of silicon which can be made into cells later.

In this way we reach a new asymptote for the price of the raw material which is about 10¢/W; a price that it will be possible to reach for the whole cell through industrialization.

Another way exists to lower the price of the Si-type cell: the preparation of Si itself.

The manufacture of ultra-pure polycrystalline Si, corresponding to the specifications necessary to the production of electronic components from Si of purity 98%, multiplies the price of the raw material by 1000. It is, then, fundamental to reexamine closely the problem of production of polycrystalline silicon. It is not obvious that the amount of impurities necessary for high quality scaling circuits is also necessary to guarantee the quality of cells of several cm^2. The cost of silicon is negligible in the total cost of the scaling circuits. In a first stage, then, the consequences of using Si of lesser quality must be analyzed on the finished product. If the conclusion is that polycrystalline Si of lower quality can be used (as seems to be done in the USSR), it will remain to obtain (and this may not be simple) from the chemical industry, a silicon product of a lower and cheaper grade.

II.2.1.2. CdS cells

It seems that the problem of the high cost of CdS cells arises partially from the fact that the initial industrial objective was to master the technology; the objective of lowering the cost remained in the background. This problem is now obvious. Industrial analysis must be pursued /19 in order to see if the technique by "evaporation" really precludes price competition with the silicon.

On the other hand, a less costly operation than evaporation might be searched for. For instance, a deposit by a chemical method might be found.

The price of the basic material, the evaporated CdS for a 1 w generator, is in the range of 10 to 20 francs. If one takes into account the fact that 90% of the powder is lost during evaporation, one gets a price of 1 to 2 francs. (if it was possible to realize a process without loss). At this price, the Cd accounts for about 1/3. It is a rare and relatively expensive material (about 50 francs per kg).

The asymptote for the price of the raw material for Cds cells is about 10 - 20¢, which is about equivalent to the price of the "thin" Si. This price is based on a thickness of 40µ for a layer of CdS. It is not certain that this thickness can be decreased, since thinner layers give rise to problems of stability (at least in the actual state of technological knowledge). To compare the prospects of the CdS cells with the Si type cells, one can conclude that they are about similar. The fact that major technical problems still must be solved in both cases does not allow a more precise forecast.

II.2.1.3. Cd Te cells

The Cd Te type cells have been extensively studied in France. The CNES developed them between 1966 and 1970 at the RTC. The economic prospects were very promising, but a problem of instability at the junction level had to be solved. The prospects of long term prices are about the same as for the CdS type. The stability problem does not seem to be insoluble.

II.2.1.4. As Ga cells

IBM in the U.S.A. has developed such cells with an output of 13 to 15%. But only a few mm^2 of cells have been realized. IBM states that the interest in these cells is exclusively on a scientific level.

The raw material for polycrystalline Ga As is 50 times more expensive than the polycrystalline Si. This is due to the high prices of the elements Ga and As, and to the process of formation. It seems very improbable that this cost will reach reasonable levels in the future. /20

Generally, Ga-As technology is very costly. It seems doubtful that cells made from this material could play an important role in the future.

II.2.1.5. Other approaches

Schottky diodes, organic moderated reactors, cells with ternary materials, cells with variable gaps.

No solar cell has been yet realized with other approaches with an output of more than a fraction of %. In spite of worldwide efforts in this direction, progress has been disappointing.

Other basic studies have to be done for many long years before one of those technologies can be applied to an industrial operation for terrestrial applications.

II.2.2. Sub-system of energy storage

II.2.2.1. Lead batteries

At present the lead cell is the cheapest. For a capacity of 600 W, the price is about \$20 - \$30. Efforts in the

United States are directed towards improvement of the life of these batteries. Very soon, apparently, cells with a lifetime guarantee of 20 years will be on the market. Their price should not be much higher than classical cells.

On a long term basis, other solutions can become necessary. In 1973, the price of lead increased 68%.

It is well known, on the other hand, that the storage of energy is a large scale problem for nuclear power plants. It is in this frame of mind that an important effort is going on towards the development of systems of large capacity and inexpensive storage. Two particular approaches are being pursued: /21

- fuel cells;
- Na-S cells.

II.2.2.2. Fuel cells

NASA, for the Gemini and Apollo programs, could not qualify the experiment as successful from the cost viewpoint.

For the space industry, the price of a H_2-O_2 cell is \$200 K - \$250 K per kW; in the laboratory it is a minimum of \$3000 per kW. (U.S. prices).

IFP in France announced a price of 700 - 1000 F/kWh using Pt as a catalyst. The output is 60%. A lifetime of 5000 hours has been demonstrated, but only on a few samples. The progress in the future might be slow.

However, this approach deserves to be followed through. The Russians seem to have better results.

The U.S. "power companies" have ordered a 21 MW unit from Pratt and Whitney to be delivered in 6 - 8 years.

A technical appraisal of the storage system by fuel cells for solar houses will be given in Supplement 1.

II.2.2.3. Na-S batteries

This cell functions at 300° C. The basic materials are cheap and abundant. The storage capacity is higher than 150 Wh/kg, and then at least five times greater than for the Pb cells.

The final refinements of these batteries are not complete, and it will probably be 10 years before they are usable.

Again, in the U.S.A., an effort is going on in that direction. /22

II.2.2.4. Other approaches

E.D.F. in France is, on the other hand, interested in the combinations:

— Zn-air, and
— Zn-Cl.

On a small scale, other solutions can also be considered:

— inertia wheel;
— compressed air, etc...

However, we are convinced that for the short and middle terms, the Pb battery is the cheapest and the more reliable solution.

II.3. Analysis of economic prospects

The object of this analysis is to estimate the market for photovoltaic cells in the area of the terrestrial applications.

II.3.1. Characteristics and constraints of solar generators

II.3.1. Geographic and space restraints

The insolation rate is the first essential constraint (see Supplement 3, also). This rate varies over the world from 1200 to 4000 hours per year — that is, from 3 to almost 11 hours per day, on the average.

In France, this time is distributed from 1600 (4 hours per day) to 2800 hours per year (8 hours per day).

This restraint of average insolation is followed by a restraint on the insolation variations. These monthly or daily variations condition the size of the storage means of the energy (buffer battery) which appear necessary in all the applications, and which cost will be added to the cost of the solar cells. /23

The second restraint regard the surface occupied by the solar cells: about 1 m^2 is needed to give 100 to 160 W in full sun.

II.3.1.2. Cost of solar generators

At the present time, RTC sells the solar panel 280 F. per "peak watt" (type Si batteries assembled).

On the American space market, the price for the finished Si-type cells varies between \$200 and \$400 per watt, half of it for the junction. On the European space market, the sale price for the cells is at least double.

For terrestrial applications, some American companies advertise finished cells for \$20 to \$40 per watt, half of which is for the junction.

For 1980, the "National Science Foundation" forsees a price of \$2 per peak watt.

The prices for generators other than the Si-type are not available at this time.

II.3.2. Classification of possible uses for solar generators.

The purpose of this section is to give a list of possible applications for the solar generator, taking into consideration the technical constraints only, but excluding the economical considerations. /24

For this, all human acitvities using a power source other than human labor itself must be considered. These activities are innumerable and cover practically all fields, so that it will be necessary to limit the description to the general categories, without going into detail.

For the requirements of this study, we will classify these activities into categories as a function, in particular, of the surface:

- the energy needs for mobile equipment;
- the energy needs for portable equipment;
- the energy needs for fixed equipment which is easily moved (congestion problem);
- the energy needs for fixed equipment.

II.3.2.1. Mobile equipment

Most moving bodies need significant power for propulsion (minimum of 50 CV $\simeq$ 36 kW for a car) which will require either ridiculously large solar cells or prohibitively long duration of battery recharge. The solar generators could then be used only as an electrical power source, or as a spare; but the use of the power source of propulsion for electricity makes it marginal but reduces the cost.

The use of the solar generator, except for maintaining the battery for long periods of non-use, can only be considered on naturally propelled bodies, such as space devices, drifting balloons, sailboats, and drifting buoys, or as an emergency system on the geostationary balloons of the Pégase type.

II.3.2.2. Difficult-to-reach areas

The energy can be used for the following: /25

— captive balloons in the atmosphere;
— fixed buoys and offshore drilling platforms.

II.3.2.3. Portable and transportable equipment

Activities which necessitate portable or transportable power operated equipment:

— military activities;
— tourism (camping);
— research activities (measures);
— public works;
— transportation (see II.3.2.1. Mobiles).

a) Military activities

Solar generators can be applied to:

- portable equipment (radio);
- field equipment.

b) Tourism and household applications

The possible applications concern equipment for the population at large, such as radios, TV, tape recorders, camping equipment, digital clocks, toys — without forgetting an application already in use, lightmeters for photography or cinema.

c) Public works

Power sources for construction yards, signals for advertising, warning signals.

d) Research activities

Production of electricity to research teams is also to be considered and represents an activity similar to the production of electricity to the construction yards. We can also note the energy necessary for portable measuring apparatus. /26

II.3.2.4. Fixed plants — remote from an electrical network

— Telecommunications (relay of Hertzian beams, radio and television, re-transmitters).

— Research activities: Essentially, automatic measurement stations for study or survey of the environment (vulcanology, hydrology, nivology, meteorology, geophysics, survey of underground water level, survey of forest fires, seismology, aeronomy).

— Activities to aid transportation: navigation aids (lighthouses, autonomous lights), aeronautics aids (radio beacons, V.O.R.), emergency stations on roads and freeways, railway signals.

II.3.2.5. Specific applications to underdeveloped areas without electricity — rural applications.

— Schools (energy for school television);
— water pumps and irrigation;
— household electricity;
— power for isolated plants (copper refining, pumping water for aquaculture).

II.3.2.6. Non-isolated areas — villages and cities with electricity.

— electricity for individual dwellings; /27
— electricity for buildings;
— electricity for commerce and industry;
— electrical power plants.

II.3.3. Cost comparison with other power sources and possibilities for photovoltaic energy.

Sources which could be competitive with the solar generator are the following:

— chemical batteries;
— hydrocarbon-thermoelectric generators;
— aerogenerators (windmills);
— low temperature solar motor;
— gasoline or diesel generators;
— periodically recharged batteries;
— main electrical supply.

It is not possible to compare directly the cost of these power sources with the cost of a solar generator, since the comparison depends greatly on the characteristics needed (maximum power, average power, availability) and on the possibility of maintenance. We will compare each of the applications listed in II.3.2., choosing as a competitor for the solar generator, the power source adapted best to the problem.

For each utilization we have estimated the actual cost of production, and computed the total cost on the lifetime of the equipment (or of the station) if it is shorter than 20 years. These calculations were computed with a rate of actualization of 10%, to take into account the difference between investments and exploitation.

The solar generator was then rated with the formula: /28
7.5 amperes (average) = 1 ampere (peak), and an equivalent cost per W of production.

This corresponds to the assumption that it is necessary to have one W permanently (24 hours out of 24) to install a generator capable of producing 7.5 A at the peak of insolation. For Heliotek and Sharp, this condition corresponds to an area with an insolation duration of about 2000 hours per year.

This is the cost that the solar generator should not exceed per watt produced in full sun (for about 100 mW/cm^2) to compete with the most economical production at the present time (which might not be the one currently in use) for the application under consideration. The cost of the storage does not apply (buffer battery), since it is a constant no matter what source of energy is used. However, the following exceptions should be noted.

— chemical or main line power sources;
— water pumping.

In these last cases, the permissible cost of the generator is less than the above, but probably by very little.

All the data can be found in Table 2. This table is based upon information given by:

— CNES studies on the collection and localization by satellite for Tiros N and Géole;

— from information given at the colloqium of UNESCO (Paris, July, 1973) "The sun at man's service".

— from the documentation "Primary sources of energy" of the CCITT, published by UIT (1970);

— from information provided by CNEXO and the Service of beacons and light houses;

— from the cost figures published by EDF in its commercial pamphlets.

A few remarks should be made about this table correspond- /33
ing to the following numbers:

(1) Thermoelectric generators can decrease the cost of this activity. The initial cost could be 1/2 lower; therefore, the equivalent cost per W for the solar generator also.

(2) This is the resale price for a solar generator for ships sold in the U.S.

(3) The marked cost is not an accepted price, and a study of the market to the public would be

Table No. 2	Average Consumption	Lifetime of the Station	Time between Visits	Power Now in Use, Competitor	Present Costs	Initial Equivalent Cost	Equivalent Power of S.G. in W	Equivalent Cost per Installed W of Present Supply (F)
1. Isolated and fixed stations (vulcanology, hydrology, nivology, meteorology, geophysics, survey of underground water level, seismology, aeronomy, forest fire survey), automatic.	0.1	10 Y	1 Y	Zn-air cells	200 F/yr	1,400 F	Low Intensity 1.5	330
2. Isolated villages. School television	35 W-40 h/ week, aver- age 8 W	20 Y		Zn-air cells	2,700 F/yr	27,000 F	60 W for H = 4000 h (Nigeria) 120 W for H = 2000 h (Europe)	420 (1) 220
3. Recharge of sailboat batteries	30 W h/ week 0.18						1	400 (2)
4. Drilling platform emergency light and sound beacons	500	10 Y		Zn-air cells	200,000 F/yr	1.4 MF	3,700 ,area app. 37 m^2	380 Generator life- time 10 years
5. Registering balloons	25-50 kW	6 months		Solar genera- tor			5.6	Acceptable present price
5. Geostations (type Pégase)	0.2	Recovered balloons					25-50 kW	Acceptable present price
6. Portable equipment for public use: - television - receivers - radios - tape recorders - camping - watches - toys - light meters (photo)	Calculated for 1 W	Average 5 years		Chemical Cells	App. .10c/ W h or 800F/ year	3,200 F	Low Intensity 15 W	about 200 (3)

Table No. 2 (continued)	Average Consumption	Lifetime of the Station	Time between Visits	Power Now in Use, Competitor	Present Costs	Initial Equivalent Cost	Equivalent Power of S.G. in W	Equivalent Cost per Installed W of Present Supply (F)
7. Emergency Road Station		20 yrs.						About 200 F
8. Signal and Train Dispatch Station		20 yrs.		ZN-air cell				About 200 F
9. Water pumps	Water supply for a village of 2000 people = 10 m^3/h. Depth 20 m. Necessary power 560 W, 6 h/day 140 W average. Lifetime 20 yrs.			Low temp. Solar motor	1 F now. Forecast 10 c/m^3. 2200 F/yr	22,000 F	1,000	Now 200 F Forecast 10 (4)
10. Fixed buoys (research hydroclimatology)	-0.180	2 yrs.	6 mo.	Chemical Cells	500 F/yr	950 F	5.6 Pyramidal Si cell 560 cm^2	170 2 yrs in use
Fixed buoys (meteo, oceanography)	0.2	2 yrs.	6 mo.	Chemical Cells	500 F/yr	950 F	5.6 as above	170 2 yrs in use
11. Transportable stations of defined location (Geole-Geoceiver)	20 to 30	10 yrs.	Few days Use 1 day out of 3	Gasoline generator. 3 yr lifetime	1200 F at installation 1-2 c/Wh or 1000-2000 F/yr	15,000 F (not includ. transport. of carburant)	230	70 3 yrs of utilization (5)
12. Relay for hertzian beams	50	20 yrs.		Thermoelectric generator. 10 yr lifetime.	8700 F + 0.1 c/Wh or 400 F/yr	19,000 F (not includ. transport. of carburant)	370	50 (6)
13. V.O.R.	100	20 yrs.		Thermoelectric generator. 10 yr lifetime.	16,000 F installation + 0.054c/Wh 400 F/yr	38,000 F	750	50 (6)
14. TV & radio transmitters	600	20 yrs.		Thermoelectric generator. 10 yr lifetime.	100,000 F + 0.05 C/Wh 2500 F/yr	190,000 F	4500	45 (6)

Table No. 2 (continued)	Average Consumption	Lifetime of the Station	Time between Visits	Power Now in Use, Competitor	Present Costs	Initial Equivalent Cost	Equivalent Power of S.G. in W	Equivalent Cost per Installed W of Present Supply (F)
15. Navigation aids Autonom. lights	60	20 yrs		Air generators 10 yr lifetime	10,000 F for equipmt.	15,000 F	450	45 (7)
Radiobeacons	50	20 yrs		Thermoelectric generators. 10 yr lifetime.	8,700 F installation + 0.05 c/Wh 200 F/yr	15,000 F	370	40 (6)
16. Drifting buoys (oceanography, meteo)	0.2	6 mo.		Chemical cells	260 F	260 F	6 Pyramidal Cell	43 Length of util. 6 mo.
17. Fixed buoys (signal)	12	10 yrs		Air generator 5 yr lifetime	6,000 F for 5 yrs.	10,000 F	330 Pyramidal Cell	27 Approx. 10 yr lifetime (7)
18. Power supply to construction yards or research teams	5 kW 40 h/wk or 1 kW average			Diesel generator	40,000 F + 0.08 c/Wh 7,000 F/yr	150,000 F	7 kW 70 m^2 cells Si	20 (5)
19. Military equipment for campaigns	Various needs							Probably 10 to 20 F
- Portable (radio)								(9)
- portable meas. equip.								(8)
20. Electricity supply to homes (Africa particularly)	500 kWh/yr 60 W average	20 yrs		1 Diesel generator per village (100 houses) 10 yr lifetime.	45,000 F + 0.084c/Wh 15,000 F/yr	460,000 F	450 W/house (4 m^2 cells Si) or 40 kW/village (400 m^2)	10 /32
21. Isolated industries refining of metals (copper)		20 yrs		Diesel generator up to 25 kW installed				10

Table No. 2 (continued)	Average Consumption	Lifetime of the Station	Time between Visits	Power Now in Use, Competitor	Present Costs	Initial Equivalent Cost	Equivalent Power of S.G. in W	Equivalent Cost per Installed W of Present Supply (F)	
22. Aquaculture, water pumps	15 kW 10 h/day 6 kW average	20 yrs		Diesel generator 10 yr lifetime	45,000 F + 0.084c/Wh 15,000 F/yr	460,000 F	45 kW or 400 m^2 Si cell	10	(5)
23. <u>Non-isolated areas</u> Electrical supply to individual houses Electricity to industrial and commercial buildings	3000 kWh/yr 350 W average	20 yrs		main el. supply	20 c/kWh 600 F/yr	6,000 F	2,500 W or 25 m^2 Si cell	2.5	
24. Electrical Power Plants	1 MW 800 h/yr 8,000 MWh/yr	20 yrs			Production cost 4 to 5 c/kWh 0.4 MF/yr	4 MF	7 MF or 0.07 km^2 Si cell	0.6	(9)

necessary to find out what it would be. This market can exist only if the extra cost of the equipment is rather low (perhaps 10 to 20%), which risks dividing by 2 or 3 the maximum cost acceptable for the solar generator.

(4) The solar engine is still in the experimental stage; we quoted the present price, and the price at which the Société Mengin, who is building it, hopes to arrive.

(5) The cost per Wh for the generating sets were estimated from the following considerations:

- 1 kWh can be produced by about 300 g of gas-oil, so that if one liter of gas-oil costs 1.20 F, the cost per Wh would be:

$$\frac{300 \times 120}{800 \times 1000} \text{ centimes} = 0.05 \text{ centimes.}$$

The value of 0.08 centime is quoted to make allowance for transportation of the fuel and maintenance.

(6) The hydrocarbon thermoelectric generators are used very little yet, but due to their advantages, they probably will be developed in the near future.

(7) The aerogenerators are still experimental and their reliability has not been proven, but we hope that they will be useful for many applications, especially on the seashore.

(8) For the military, the main interest in solar generators is their autonomy, which would eliminate the problems of logistics. /34

(9) According to the EDF, the average resale price of a kWh is 20 centimes, but the production cost is only about 5 centimes.

SIMPLIFIED CLASSIFICATION OF TABLE 2

			Guide-Prices (per watt)
1.	Isolated and fixed sol stations		930 F.
2.	Supply for school television sets		420 F.
3.	Recharge of sailboat batteriss		400 F.
4.	Drilling platforms		380 F.
5.	Balloons		300 F.
6.	Portable equipment for public use	(variable)	200 F.
7.	Roads and freeway emergency stations		200 F.
8.	Railway signals		200 F.
9.	Water pumps		200 F.
10.	Fixed buoys		170 F.
11.	Transportable position reference stations (Géole)		70 F.
12.	Relay of Hertzian beams		50 F.
13.	V. O. R.		50 F.
14.	Television re-transmitter		45 F.
15.	Navigation aids (fixed lights, radiobeacons)		45 F.
16.	Drifting buoys		43 F.
17.	Fixed buoys (signaling)		27 F.
18.	Electricity for construction yards		20 F.
19.	Military campaign equipment		10 to 20 F.
20.	Housing in Africa		10 F.
21.	Isolated plants		10 F.
22.	Aquaculture		10 F.
23.	Housing in France		2 F. 50
24.	Electrical power plants		0 F. 60

General Remarks Concerning Table 2, and First Conclusions on the Market for Solar Generators

a) With the price of $20/watt claimed by the U.S.A., it will be possible to extend the market up to the section 10 included. /36

The price of $2/watt foreseen by the U.S.A. for 1980 would open up the entire market, except for EDF. The general evolution of competition for solar energy is presented in Figures 2 and 3.

The market accessible today is the chemical cells market.

Another important utilization group will be reached from section 11 for a competitive price for generating sets, and, in particular cases, aerogenerators and thermoelectric generators.

Finally, solar generators will compete with conventional power when their cost is 1 - 2 F/watt; therefore, certainly not for another 10 years, except in certain cases where the consumer will pay for the network connection (cost in the range 20,000 - 40,000 F per km wire), which cost will appear high as the needed power decreases.

The installation of electric power plants with solar cells does not appear to be economically worthwhile, if the costs of the distribution and transportation are taken into account in the prime cost.

b) The figures quoted are only in the average range, and must be modulated, particularly as a function of the geographic location (sun) of the position of the network, and the financial possibilities.

c) The classification given in Table 2 is only a first approach with a fairly large uncertainty factor.

In general, we have adopted a cautious attitude reflected, in particular, in the unfavorable forecasts for: /37

— relays for Hertzian beams;
— navigation aids;
— fixed buoys;

which are, respectively, in positions 12, 15, and 17. We know, however, that solar generators have been ordered for these purposes.

It goes without saying that the section 5 — portable equipment for the public — will require much more detailed analysis than the one presented here.

Here are a few qualitative criteria which reinforce the attraction of the photovoltaic generators:

— For the portable systems, the chemical cells are usually much heavier than the solar generators. They must be replaced frequently. After use, it is impossible to just throw them away because of pollution (important for the drilling operations at sea).

— the diesel groups have a limited reliability and require a quasi-constant survey. In certain countries, the broken-down units cannot be repaired for lack of qualified personnel. It is well known that for a single installation TRT sets up three groups: one functioning, on in "stand by", and a spare one. This is not accounted for in our table.

In addition, the supply adds cost problems and, in certain cases, a problem of access.

d) Analysis of the solar generator market gives the choice between a piece of equipment representing a large investment, or cheaper equipment requiring high upkeep costs.

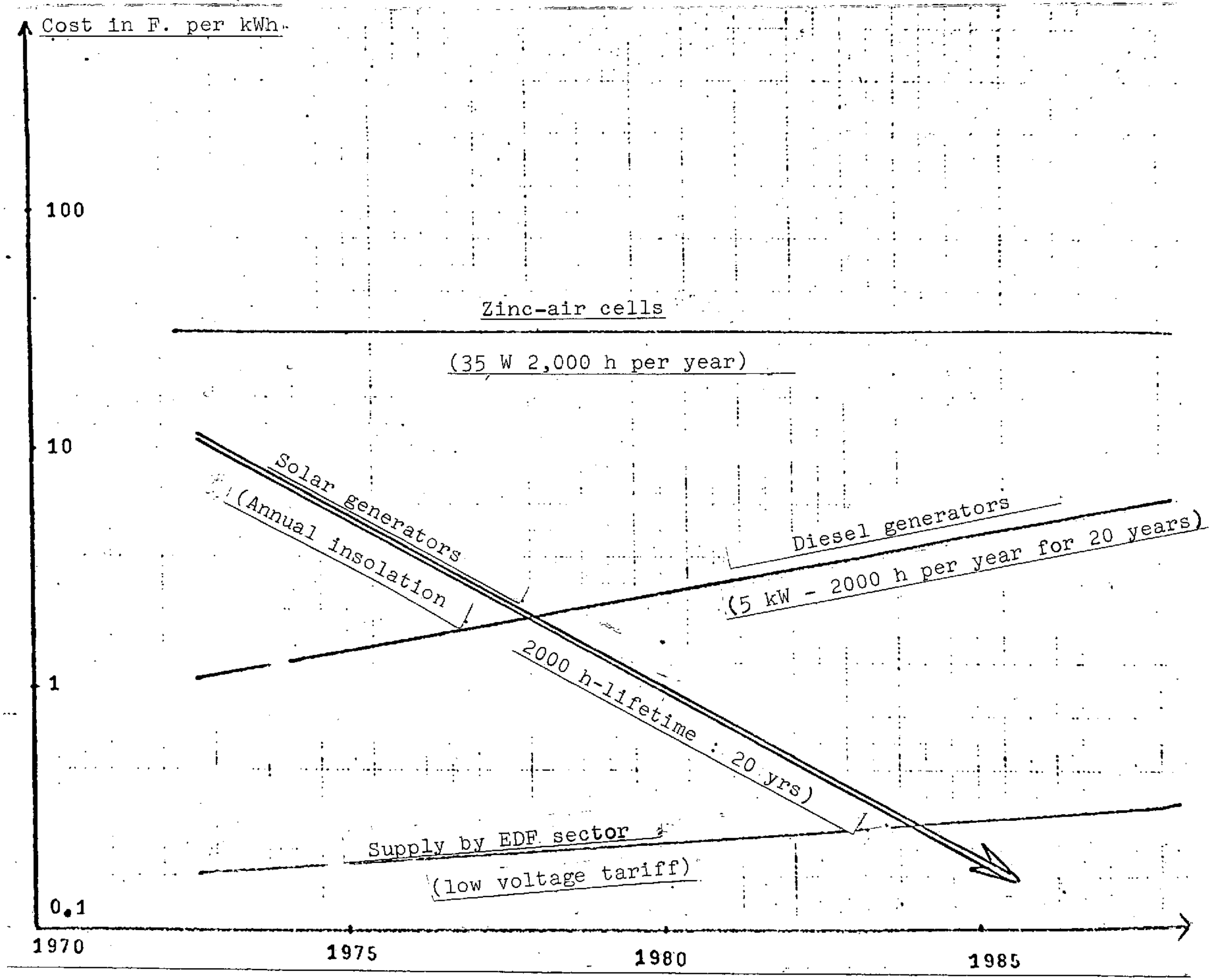


Figure 1. Cost of energy

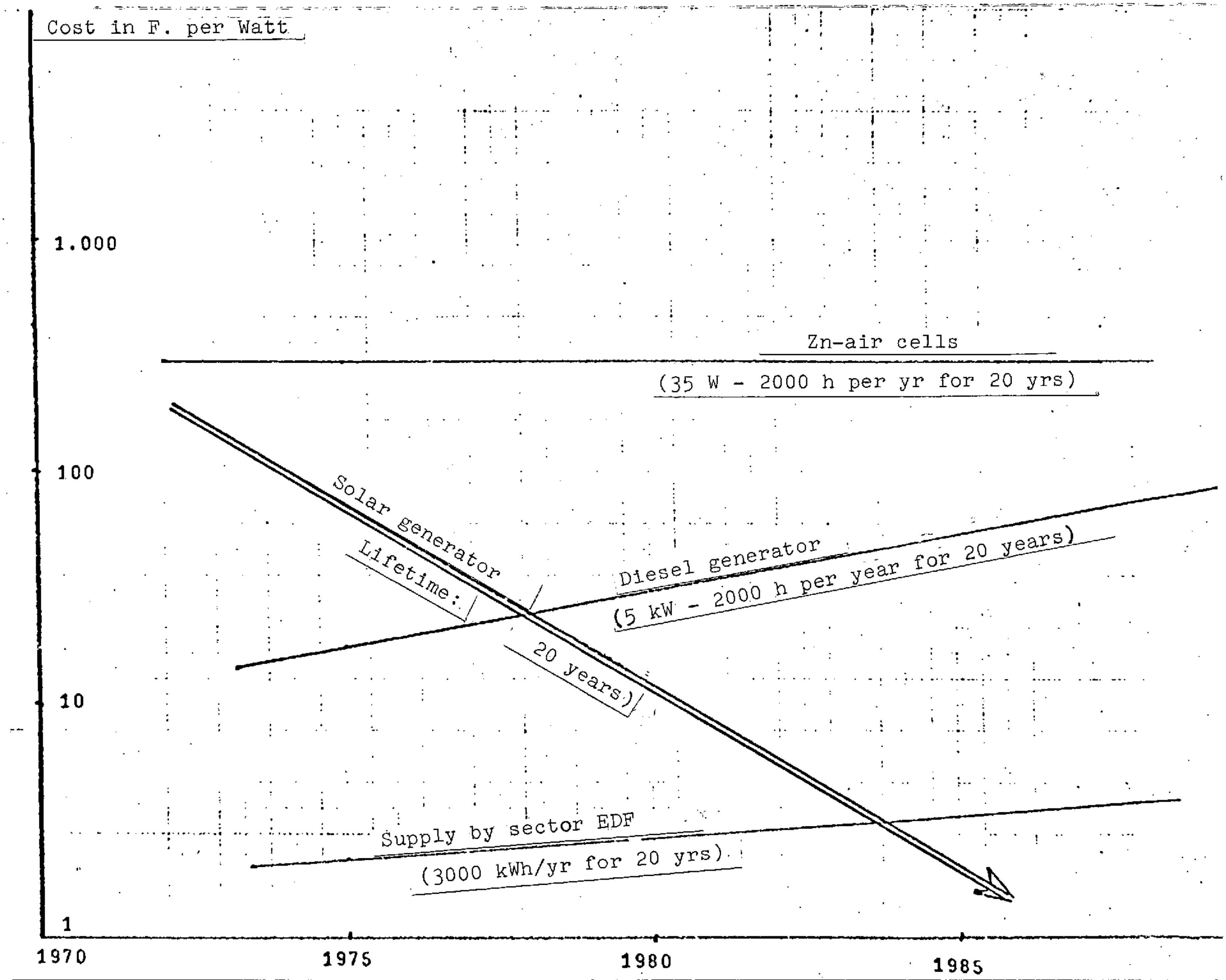


Figure 2. Cost equivalent per installed watt

TABLE 3

ANNUAL MARKET IN NUMBER OF EQUIPMENTS (OR STATIONS) MANUFACTURED

APPLICATIONS	Geogr. Area	1974	1975	1976	1977	1978	1979	1980	1985	1990
1-Drifting balloon	World	200	250 (NIMBUS F)	1000	1000 (GARP)	200	250	300	300	300
2-Geostation balloon PEGASE	France	-	-	-	-	-	1	4	4	4
3-Fixed buoys (res., hydroclimatology, meteo, oceanogr.)	World	60	60 (NIMBUS F)	10	200	225	250	280	310	350
4-Fixed buoys(signal)	France	100	100	110	120	130	140	150	150	150
5-Drifting buoys	World	100	100 (NIMBUS F)	10	160	160	180	200	210	220
6-Sailboats(recharg. batteries)	Europe			1000 per year						
7-Drilling platforms	World	250	300 (number of platforms in operation)	350	400	450	500	550	650	700
8-Transportable sta. of defined location	World	30	40	50	60	70	80	80	80	80
9-Emergency transport. Stations of telecom.	World	-	-	-	-	-	-	5 from 1980 to 1990 i.e. 1/2 per year average.		
10-Power sources to Construction yards or Research teams	France	1000	1000	1000	1000	1000	1000	1000	1000	1000
11-Portable military equipment -campaign equipm.										
12-Portable measur. apparatus										
13-Equipment to the Public										

TABLE 3 (continued)

APPLICATIONS	Geogr. Area.	1974	1975	1976	1977	1978	1979	198o	1985	1990
14-Isolated ground sta. fixed & automatic.	World	20	50	300	1600	1800	1800	1900	200	20
15-Relay for hertzian beam	French speak. Africa	3000		(Number of relays in operation)					9000	1000
	France							600	1200	250
16-TV & Radio tranmit.	French speak. Africa		(number of transmitters in operation)	20				40	80	10
17-Autonom. lights	France	10	20	20	30	30	40	50	50	50
18-Radiobeacons aer.	French speak. Africa	250	250	250	250	250	250	250	250	250
			(number of equipments in operation)							
19- V.O.R.	Fr.sp. Africa	-	1	1	1	1	1	1	1	1
20-Emergency sta. on highways	France	40	40	40	40	40	40	40	40	40
21-Signal. for railw.	France		3000 in operation							
22-School TV			see Table 1 (supplement 2)							
23-Water Pumps	Africa		(number of pumps in operation)					4500		20000
	India							6000		30000
	Centr.& South America							3000		15000
24-Electr. for houses in isolated villages	Africa		(number of villages to equip)					4500		20000
	India							6000		30000
	Centr.& South America							3000		15000
25-Isolat. Industry		–	–	–	–	–	–	–	–	–
26- Individual houses	Europe		see Table 2 (supplement 2)							
27-Industr. & commerc. buildings										
28-Power Plants										

We take this into account by introducing a monetary rate in our estimates, but this method is not perfect because it requires the consumer to find the necessary credit.

II.3.4. Quantitative estimate of the market for solar generators (non-space)

A. A quantitative estimate of the market for solar generators in the coming years is attempted. This market will depend on the current prices, but also on many parameters, as mentioned above, and perhaps on political considerations, in particular those tied to the energy crisis. We will try to estimate a potential market for each listed application, defining those closest to each other. This market will be worldwide in some cases, partial in others: the geographic extent of the market will be indicated in each case.

Dry batteries constitute the more available market. To give an idea of the importance of this market, one must quote the figure of $1 billion for the sale of electrochemical cells of all types on the U.S. market in 1973.

The impact of the photovoltaic generators, which for many applications are already competitive with dry batteries, could be considerable in 5 years, a minimum delay for the introduction of a new technology to a market.

Table 3 is a summary for the coming years of the estimates for the various areas.

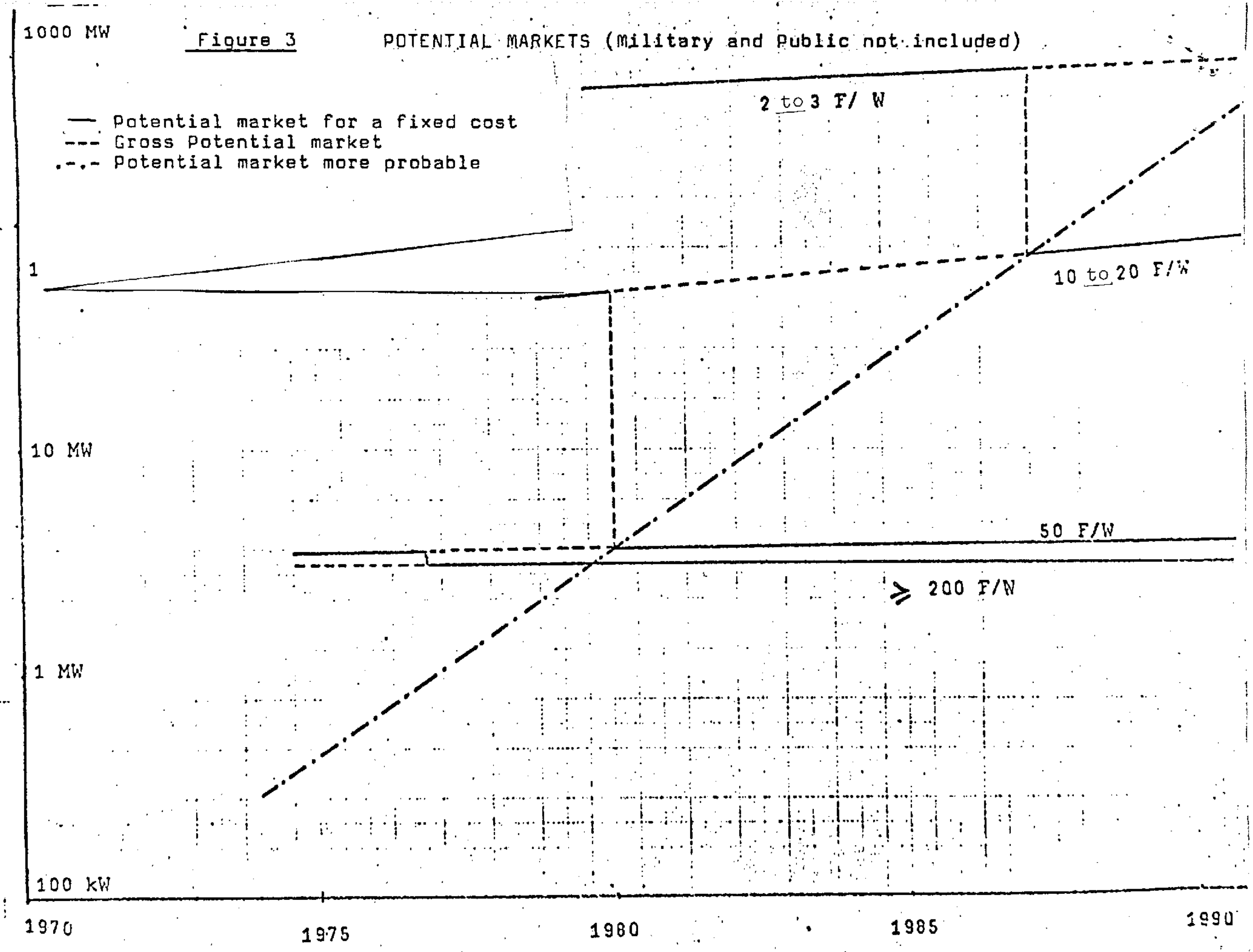
B. From Table 3, and in consideration of the information on cost and power equivalent for the solar generators described in Table 2, we compiled Figure 4, showing the potential market as a function of year for the various costs of solar generators. /43

In addition, the following hypotheses have been made:

— when the geographic extent indicated is worldwide, we can count on 20% of the market in French-speaking Africa, 100% in France, 2/3 of the European market; 50% in Africa; 30% in India, South and Central America, and Arab countries. These figures are questionable, but necessary, to a first estimate; they should be revised when the industrial structure and prices are better known.

— as far as the equipment already in existence, we assumed that the solar generators would be introduced at the time of renewal of the equipment.

The forecast of cost decreases indicated on Figure 3 was then used to determine the curve of the yearly gross potential market. In fact, the market will not materialize immediately after the price of the solar generators becomes competitive; there will be some inertia, then a lag phase due to the adaptation to the market of a new product. We can assume that the gross potential market for a given cost will be reached when the price of the solar generator arrives at the following range of prices, that is, with a 5-year delay. As far as school televison sets are concerned, the projected figures of 50,000 sets per year (or 3.6 MW) cannot certainly be reached rapidly because of financial reasons, which will be less crucial when the cost will be 10 to 20 F., at which time we think the figure of 50,000 will be attained. In the near future (1975), it does not seem realistic to surpass 10% of the indicated values, that is, about 250 kW, if we consider problems of financing and the present prices for power sources adapted to this need. To this figure, 140 kW must be added for other applications, i.e., about 500 kW.


1000 MW
Figure 3
POTENTIAL MARKETS (Military and Public not included)
— Potential market for a fixed cost
--- Gross Potential market
.-.- Potential market more probable
2 to 3 F/ W
1
10 to 20 F/W
10 MW
50 F/W
≥ 200 F/W
1 MW
100 kW
1970
1975
1980
1985
1990

II.3.5. Conclusion

This rapid study leads to the following conclusions: the annual potential market for solar generators adapted to terrestrial applications for the French industry is around 500 kW for 1975, 4 MW — around 1980; 80 MW — around 1987, and reaches hundreds of MW around 1990, if we take into account the hypothesis on the evolution of price forecasts (see Figure 3). These estimates are approximate, and do not include the military and public markets for which we are unable to give a good figure, although they appear to be substantial because of their qualities of longevity and autonomy of the solar generators. /45

On many points, a longer and more detailed study seems necessary to insure a better credibility.

III. FUTURE PROSPECTS IN FRANCE AND IN FOREIGN COUNTRIES, AND TECHNICAL ORIENTATION

III.1. Potential studies and available technologies

The program of studies and development defined and followed by the CNES, aided at the beginning by research results financed by the CNRS and DGRST on cells, has been centered for ten years, on one hand, on studies of monocrystalline silicon photocells, thin slabs of cadmium sulfide and cadmium telluride, and on cells with variable gaps; and, on the other hand, on the development of silicon photocells. /46

The research was conducted by close association of industrial and university laboratories. This collaboration has been very profitable.

The present situation can be summarized as follows.

III.1.1. Photocells

III.1.1.1. Industry

a) Silicon

SAT — manufacture of photocells with a 10 - 11% yield AMO for space needs;

— mastering the technology of high performance cells (12 - 13% AMO);

RTC — manufacture of photocells for terrestrial applications of 12% yield AMI (10% with anti-reflecting layer).

b) Cadmium sulfide

SAT — study and development of photocells with thin layers of cadmium sulfide. The output is in the range of 6 - 7% AMI. A small unit of production exists.

c) Cadmium telluride

RTC — pilot manufacturing experiment dismantled three years ago. /47

III.1.1.2. Research laboratories with well-established experience in the photogenerator field

DERTS (Toulouse)
- Study of effects of space (UV radiation).
- Study of character determination and simulated experiments on computers.

CESR (Toulouse)
- Character determination.

LETI (Grenoble)
- Study of radiation effects of particles (electrons, protons, neutrons).
- Study of new structures.

LEP (Limeil-Brévannes)
- General competence with the Si type.

CNES (Toulouse laboratories)
- Help in designing and testing.

School of Chemistry (Paris)
- Study of Cu^2S.

University of Montpelier

— Study of CdS, CdTe, Cu^2S, CuTe.

University of Nancy

— Study of thin slabs of CdS. /48

— Study of Cu diffusion.

— Study of the junction CdS - Cu^2S

Laboratory of Physics of Solids of the CNRS (Bellevue)

— Study of variable gap cells (CNRS Contract terminated around 1970).

The object of all this research is to study space applications of photogenerators. Consequently, the directions of research were chosen in order to obtain a specific power as high as possible and, on the other hand, a longer lifetime in space.

This explains the efforts directed towards the thinness of silicon photocells of square or rectangular section, the effects of UV radiation, of the electrons, protons, increasing the output, effects of the important thermal cycles.

The research and development teams formed for this program have acquired a high competency on the technical as well as scientific levels. They are now able to continue the research in the directions imposed by terrestrial applications: decrease of the electric watt price, behavior in terrestrial atmosphere (humidity, dust, etc...).

III.1.2. Storage system

SAFT can produce some cells and study more optimal batteries in association with the CGE for this particular use when the charging and discharging cycles are slow and of weak intensity.

III.2. Development programs in foreign countries

A number of countries have already started programs of development of terrestrial application of solar energy. The importance of these programs led to forecasts of a very rapid evolution of the corresponding international market. /49

The Japanese center for Foreign Trade reports that Japan plans to invest in this field in 1974 $7 million, within the frame of a program entitled "Luminosity of the Sun".

The U.S.A. has a budget of $2.6 million for the development of photovoltaic generators only, in 1974, and forecasts a budget of $8 million in 1975 (fiscal year starting July, 1974).

— American industry has already at its dispositon the means of manufacturing high performance Si cells which permit very competitive prices for the panels.

— This industry will make rapid strides because:

- the U.S.A. seems to be willing to develop at all costs new power sources, among which is solar energy: the amount of the budget for this purpose is significant;
- the U.S. domestic market is easily accessible and sizable;
- fiscal measures (the panel price or the budget invested in "solar industry" are tax deductible) are under study and are a very strong promotion factor;
- in vast areas of the American mainland, the rate of insolation is similar to or higher than the most favorable regions of Africa;
- with the aforementioned large budget, the chances of success of the American industry in such a critical area as ultrathin Si cell development are extremely good.

On the other hand, it seems that:

— the market in metropolitan France, smaller than the American market, will require a change in the way of thinking; consequently, a delay in time will occur for the development of this market at the national level.

III.3. Possible technical orientations

The analysis of the present situation described in this chapter indicates that a relatively important market for silicon panels could now be achieved; at this technical level, they are the only ones well developed. /50

It does not seem that the thin slab CdS or CdTe generators could become commercially competitive for the next 3 years.

It might be possible to sell at present some generators requiring mostly an industrialization, completed in part by modest help from university or para-university laboratories.

The panels would be an assembly of Si cells with an output in the range of 15% AM1, if possible without anti-reflection layer. The process of manufacture should be as simple as possible. The raw material Si would be used as circular slices of at least 5 cm diameter, and thickness 200 - 300 μ.

In a first phase the process of preparation could be on a small "artisan" basis, and eventually become progressively automated.

For the protective layer, resins or plexiglass seem advisable. A number of modules of standard size could be defined accordint to the needs of the market.

Following a more detailed inquiry of potential customers, problems such as concentrators and permanent or partial orientation toward the Sun should be studied.

In parallel, a program with a 5 year goal should be started. This effort should be directed towards the development of thin slab cells, essentially on the basis of the techniques for CdS and Cd Te already available in France. /51

In view of these facts, it seem fruitless to engage in research towards completely new technical solutions.

On a long term basis, a price level equal or inferior to 10 F./watt should be reached. New techniques should be oriented to the reduction of the thickness of the cells. For the Si type, the ideas and designs to slenderize the slabs are abundant. It is the same for new processes of chemical deposition of CdS. Other materials also could be considered.

The activity toward this long term goal should be shared fairly by industry and university laboratories.

As the technical results toward a cost decrease proceed, they must be integrated in industrial flow-production.

We will conclude with a few comments on the role of the "pilot installations". A number of pilot generators must be placed on the market with the double goal of:

— advertising the photovoltaic generators about which, undoubtedly, very little is known by potential customers;

— creating better competence in industry for design of the systems. To know the exact rate of insolation and the probable charging and recharging cycles of the cell, there is no better way than to install a real one on the site of itilization itself.

First we propose to introduce the solar generators in the national — then, later, international — network of meteorology, from whence the data on the rate of insolation are compiled.

The generators would allow considerable expansion of meteorological data networks, collecting data at reasonable cost. /52
It is obvious that panel manufacutrers would be the first to benefit from the exact information still lacking concerning the variations of insolation.

Other model installations could be realized in small numbers. They must be introduced to the public (TV, movies, exhibits, etc.) and to potential French and foreign customers.

The pilot panels could cover all available markets now, or in a few years. In particular, the panels mounted on the following apparatus could be found (see list in Section II.3).

1. Meteorological stations, vulcanology, hydrology, nivology, geophysics, underground water survey, forest fires survey, (e.g., in Corsica).

2. Sailboat batteries.

3. Transistorized radio and TV, cameras, tape recorders, camping (a solar tent...), digital clocks, lightmeters, toys (electric train...), emergency lights for cars and camping.

4. Emergency stations on highways, supply to light signals.

5. Railway signals.

6. Water pumping stations (now in progress at the LEP).

7. Buoys of all kinds.

8. TV transmitters.

9. Power supply for construction yards (e.g., light signals).

10. Military systems.

11. Integration of a panel in a prototype solar house (on this subject, see the CdS panel integrated in a solar house built by Professor Boer in Newark, Delaware, U.S.A.)

SUPPLEMENT 1

HYDROGEN STORAGE OF ELECTRIC POWER PRODUCED BY SOLAR CELLS*

The amount of electric power produced by a solar generator panel of 100 m^2, installed on an individual dwelling is estimated at 750 kWh per month, on the average, for illumination conditions of a moderate climate. /53

Some of this energy can be used directly, but some of it must be stored for use at night, and to compensate the lack of production during days with little or no sun.

In order to describe the conditions of storage, the range of needs for domestic uses must be defined:

— monthly consumption: 200 kWh;
— maximum power requested from the installation: 5 kWh;
— necessary storage: one week consumption, 50 kWh.

On the other hand, the maximum power produced by the solar generator can be estimated to be 10 kW (lighting: 1 kWm^{-2}, photovoltaic yield: 10%).

Storage of one week's power will require 85 Pb accumulators of 12 V - 50 Ah, which would produce the maximum required power. Investment in accumulators increases with storage increase; for this reason, a new line of storage devices based on the hydrogen cycle is now being submitted: the electrical power to be stored disintegrates water by electrolysis into hydrogen — which is stored — and oxygen — which is not. The the electric power is restored in a hydrogen-air cell. One cubic meter of hydrogen under normal conditions (1 atm, 15° C) corresponds to the storage of 2400 Ah.

*J. Vedel, Research Director, CNRS, School of Chemistry, Paris.

The present fuel batteries deliver a voltage of approximately 0.8 V, so that 1 m^3 hydrogen allows the storage of 2 kWh. One week's consumption is then equivalent to a volume of 25 m^3 hydrogen, which should be compressed in storage. For example, the classical 50 liter hydrogen tanks contain 10 m^3 normal hydrogen under a pressure of 200 bars. The hydrogen storage has the advantage of using cheap material (water), and later, the increase of storage capacity only requires modification of the tank.

Finally, in case of long period without sun, it might be possible to use commercial hydrogen bottles for emergency reserves. Figure 1 presents the simplified diagram of such an installation.

Electrolysis of water into hydrogen and oxygen and recombination of these gases into water with energy output are electrochemical reactions which can be expressed by:

$$H_2O + 2e \underset{2}{\overset{1}{\rightleftarrows}} H_2\uparrow = 2OH^-$$

$$H_2O - 2e \overset{1}{\rightleftarrows} 2H^+ + \frac{1}{2}O_2\uparrow$$

where 1 is the electrolysis, and 2 — the production of water.

Figure 1. Schematic representation of electricity storage in hydrogen cycle /55

Part of the produced energy by the solar generator goes to the transformer, which produces the alternating current used by the domestic network, and the compressor. The other part goes to the electrolysis apparatus. The hydrogen produced is purified, compressed, and put in storage. In night utilization, the hydrogen is released, directed toward the hydrogen-air battery, which puts out a direct current to the transformer. The operation is noiseless. A system of automatic regulation must control the whole apparatus.

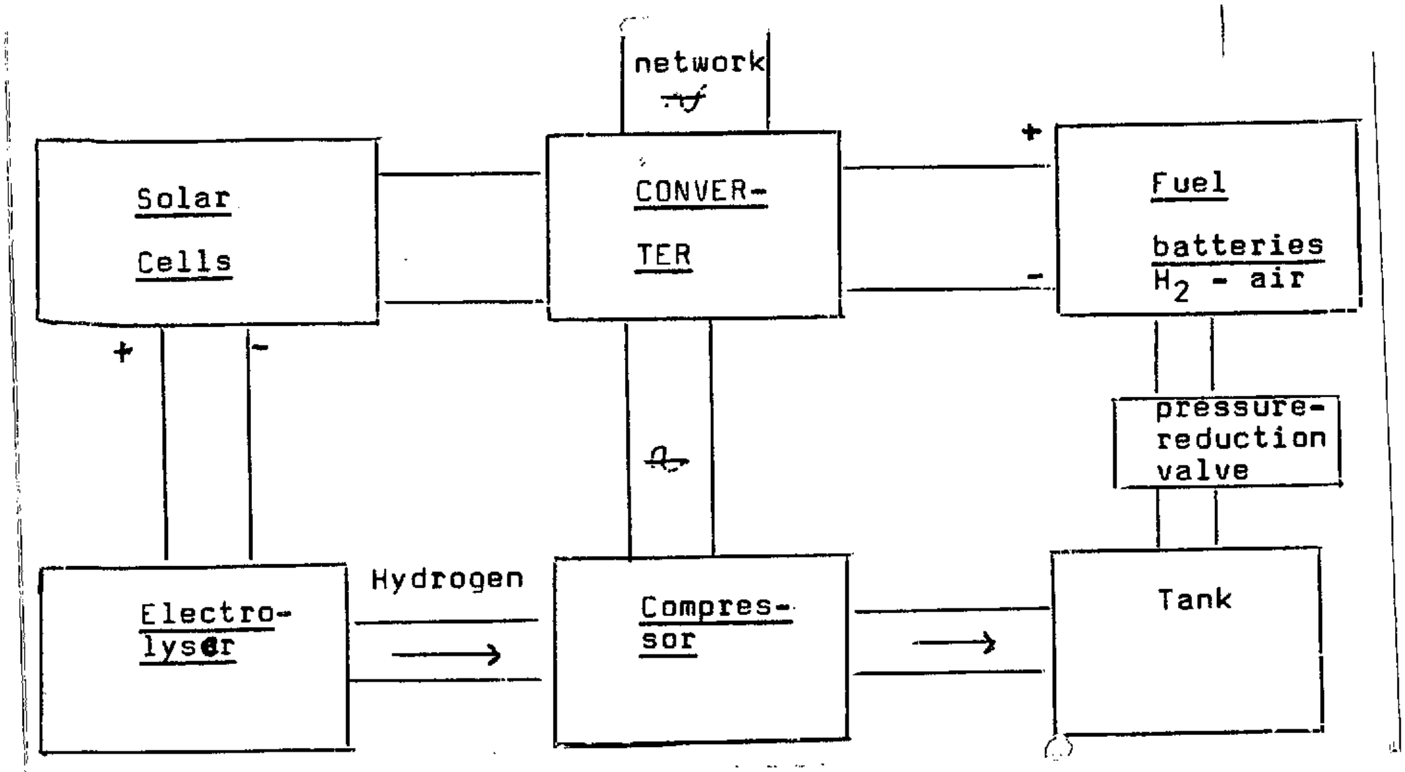


Figure 1.

At 25° C, under apressure of 1 atm, the reversible decomposition potential of water is equal to 1.23 V, but since the electrochemical reactions are irreversible, it is necessary to apply a potential greater than 1.23 to produce hydrogen, although the fuel battery only produces electricity for a voltage less than 1.23 V.

The causes of this irreversibility are the ohmic drop in the electrolyte and phenomena of a more specifically electrochemical nature known as "overvoltages".

The ohmic drop occurs in the electrolyte and in the diaphragm separating the anodic and cathodic compartments. The electrolyte must be chosen to give a maximum conductivity compatible with the resistance of the material in contact with the corrosion. In general, solutions of soda and potash are used. The gas released by electrolysis is expelled in bubbles within the electrolytic fluid, and increases its resistivity.

Conversely, it is necessary to ensure good contact between the solid phase (electrode), the aqueous phase, and the gaseous phase.

Stirring the electrolyte, a favorable factor in the electrode, minimizes these disadvantages.

The overvoltage of activation finds its source in the slowness of the electrochemical reaction, which is not fast enough to ensure thermodynamic equilibrium at each instant. It decreases with the temperature and depends on the catalytic properties of the metal of the electrode: it is minimal for platinum-plated electrodes. /56

The overvoltage of concentration is due to the change in composition of the electrolyte near the electrodes. The formed ions must diffuse within the solution in order to meet. This effect is minimized by raising the temperature and stirring the solution.

These two overvoltages increase when the density of current is raised, so that for high intensities, more energy is needed to obtain the same hydrogen quantity, even though the same quantity of hydrogen gives less energy to the cell. This brings forth the problem of suitable size for the electrodes. Other problems arise regarding diffusion of the gases reacting or formed near one electrode toward the other electrode. This diffusion is stopped by an appropriate diaphragm.

A few examples of realization are now presented.

Electrolyser

Three types of electrolysers are available:

— electrolyser with unipolar electrode, each electrode functioning either as anode or as cathode;

— filter press electrolysers or those with bipolar electrodes, each electrode functioning on one side as a cathode, and on the other face as an anode. The electrodes are connected in tandem;

— electrolysers under pressure. Electrolysers for use in special conditions (production of oxygen in submarines).

The performances of certain electrolysers are published in the table following.

Improvement of the yield

These electrolysers have already been subjected to optimization at the industrial level. However, water electrolysis is an endothermic reaction, and it is necessary to warm the electrolyte which cools.

In general, this warming is performed by Joule effect, the quantity of energy consumed corresponds to an increase in input voltage of 0.25 V per unit of electrolyte. Warming the electrolyte by solar energy not transformed into electricity would probably cause an improvement in the electrolysis yield. (Ex.: 3.7 instead of 4.2 kWh m^{-3}).

The fuel cell

The hydrogen-air fuel cells are less developed than the electrolysers. However, the French Institute for Petroleum has designed and built a modular system which, with a volume of 5 dm^3, and weight of 5 kg, has a power of 530 watts. Cells with a nominal power of 5 kW and maximal power of 9 kW, weighing 110 kg, are being built now. The lifetime should be several years in intermittent use (B. Sale, The Future of Fuel Cells, Het engineer blad, Vol. 42 (6), 1973, p. 154).

Electro-lyser	Type (1)	Consumed Power kW	Input Tension V	Output per Hour d' H_2 $m^3 h^{-1}$	Tempe rature °C	yield kWh / m^3 d' H_2
KNOWLES	E.U.	9	1.9	2.06	80°C	4.15
STUART	E.U	10	2.04	2.4	85°C	4.9
C J B	FP	1000	171	240	80°C	4.75
OERLIKON	FP	800	126	210	75°C	4.4
MORITZ	FP	180	220	40	60°C	4.4
CJB (2)	Pr	8.75	70	2	65°C	4.4
TREADWELL OXYGEN GENERATOR (3)	Pr	2.25	3	0.31	90°C	7.2

(1) E.E. — unipolar electrodes; FP — filter press; Pr — electrolysers under pressure.

(2) Pressure of utilization: 30 atm.

(3) Pressure of utilization: 200 atm.

Generally, the electrolyte is a 25% solution of potash.

Filter-press type electrolysers are now at the industrial production level. Unipolar electrode elements, conversely, appear adapted to the problems of energy storage precisely in the range produced by solar generators. Certain electrolysers under pressure seem appropriate, particularly since they produce hydrogen already compressed.

At a pressure of 30 bars, energy storage for one week occupies a space of about 1 m^3.

The yield of the fuel cells varies with the output of intensity. At maximum power, it is about 0.5. In the example mentioned above, the yield would be about 0.65, which means that the output voltage should be about 0.8 V, so that 1 m^3 hydrogen restores about 2 kWh.

CONCLUSION

In considering these figures, it is possible to give a first estimate of the output of the "hydrogen line", without accounting for either the energy consumed for automation of the system or for the compression of hydrogen, or for the gain carried out by utilization of solar thermal energy to warm up the electrolyser or the cell. It is in the range of 0.45 to 0.5 (4.4 kWh $\rightarrow$ 1 m^3 H^2 $\rightarrow$ 2 kWh), and from the initial 750 monthly kWh, only 350 kWh would be left, which is sufficient if one considers the needs mentioned above.

Furthermore, it is interesting to report that the elements necessary to this storage are in existence: elementary units for /59
industrial electrolyser, fuel cells now being built, which would favor, if not a full scale experimental study, at least a more precise evaluation of the possibilities offered by the yields.

SUPPLEMENT 2

ATTEMPT TO QUANTIFY THE MARKET IN DIFFERENT FIELDS

1. Registering balloons

In general, these balloons are already supplied by solar generators. The estimate of their number comes from studies by the CNES on the collection of data and the localization by satellites (Tiron N and Météostat). /60

A date stands out: 1977, date of the total experiment of the GARP.

2. Geostationary balloons

We have noted here the conclusions of work accomplished by various administrations (ONERA, PTT, ORTF, CNES) on the balloon type Pégase, used as platforms for the repeaters for telecommunications at moderate distances (local systems). The development of this system has not yet been determined.

3, 4. Fixed buoys for meteorology and signals

The market for fixed buoys is practically nonexistent at the present time, except as signaling devices (autonomous lights). For this application, the figures indicated come from the Department of Lighthouses and Beacons.

The use of fixed buoys for research, hydroclimatology, meteorology and oceanography is a growing activity, for which we have used the CNES studies mentioned in Item 1. The buoys located at high latitudes will not be able to use solar generators because of the insolation. We think that one-third of the buoys will be in this category, and the effect of this restriction factor on the market must be considered.

5. Drifting buoys

The facts mentioned above for fixed buoys apply here also. /61

6. Sailboats (rechargeable batteries)

It is difficult to give a figure because of the lack of data, on one hand, and, on the other, because it concerns the public, whose reaction to a new product is often more psychological than economic and which depends a great deal on advertising. We will give only one figure: 300,000 sailboats built each year in the United States. Among those, probably only 10,000 have a rechargeable battery. Taking into account the standard of living in Europe, this factor must be divided by 10.

7. Drilling platforms (emergency signaling)

There are now 250 to 300 drilling platforms, and the forecast for 1982 is 600 - 650; for 1990 — 700 - 800. The growth will probably drop by 1985. Supposedly, a solar generator could be installed on an already-built platform. The interested geographic areas are the Gulf of Mexico, the North Sea, the Persian Gulf, South America and the Gulf of Guinea. The only place where the insolation might be insufficient is the North Sea, representing 20% of the platforms (information given by the Society Forex-Neptune).

8. Transportable stations of defined location

The estimates are given by the CNES from studies on the precise localization by satellite (for Geole). We think that only 2/3 of the stations will be able to use the solar generators because of the geographic zones of utilization. This activity is only starting: utilization of Transit Satellites with Geoceiver, and, around 1980, system Geole.

9. Transportable emergency stations for telecommunications:

Source: UIT

10. Power sources for public construction yards or research teams /51

We have no information on the number of generating sets in service. We think that in France there are about 10,000 generators, but this figure has not been checked. The lifetime being about 10 years for diesel generators, and if the number of construction yards does not increase, we will have about 1000 sets renewed each year.

The research teams represent a marginal activity.

11. Military equipment

We have no valid figure to propose.

12. Portable equipment for the public

See the above notes concerning the public.

13. Portable measurement apparatus

Same remark

14. Fixed and isolated stations on the ground

We will employ once more the satellite data from the CNES studies on collection of data by satellite for Tiros and Météostat. There are small stations for study of the environment, vulcanology, hydrology, geophysics, underground water survey, forest fires surveys.

15. Relays for Hertzian beams

In France, the number of relays for local connections is in the range of 3000, and will certainly expand to more than 10,000 by 1990.

In French-speaking Africa, the number of Hertzian relays for telecommunications seems to be around 200, and 100 for television.

16. Re-transmitters for television and radio broadcast /63

The number of transmitters for television and radio of low power will be about 20 in 1975 - 1976 in French-speaking Africa.

17. Autonomous lights

The information comes from the Department of Lighthouses and Beacons, which forecasts a need for 500 autonomous lights for the decade 1980 - 1990, i.e., an average of 50 per year. For the period before 1980, we indicated an arbitrary decrease.

18, 19. Radiobeacons and V.O.R.

Forecasts obtained from ASECNA applicable to Africa. The number of 250 radiobeacons will not be increased, but the number of V.O.R. will go from 10 to 15 between 1980 and 1990 (average of one per year). At present, only a few units are in operation. It might be possible to change the power supply of this equipment.

20, 21. Highway and freeway emergency stations, signals and dispatch centers for trains

We do not have precise information concerning these activities because, for lack of time, no inquiry was made at the interested Departments. Let us try to give an approximate estimate:

— freeways: 400 km per year in France; if one emergency post is placed every 10 km, this means 40 units per year;

— railways: network of 50,000 km, approximately; a light every 1.5 km, i.e., 30,000 lights total; 1/10 only can use generators because of urban zones and location (tunnels, side of the embankment).

22. Supply to school television

We will study mainly the following countries: /64

— Africa south of the Sahara;
— India;
— South America;
— Arab countries.

Some experiments have been made in Nigeria in 1972 in areas lacking electricity.

— African countries south of the Sahara (Report UNESCO: African countries south of the Sahara, December, 197*)

The forecast for 1990 is 700,000 television sets; 610,000 necessitating an autonomous power source. The total number of telespectators would then be 130 million, 60% for school education and 40% for adult education.

— India (Report of the Organization for Indian Space Research, August, 1972)

India has 560,000 villages in which 80% of the population is living. The forecast of 50,000 sets in 1980, if there is an annual growth of 5%, foresees 814,000 television sets in 1990.

*Translator's Note: Number excluded from foreign text.

This rate sounds reasonable if we consider the increase of population and, on the other hand, the effects of concentration in the cities.

The number of receivers today is almost negligible; we can hope for a potential 800,000 sets supplied by solar power in 1990.

— Arab countries*

The information published is for 1972. The Arab States represent about 120 million people and 3,300,000 television sets. If the rate of growth in receivers is slow (about 3%), we will count about 4,200,000 sets by 1980, and 5,600,000 by 1990. We can also state the hypothesis that all sets installed up to 1972 having a power source, only those installed after 1976 will need power. At the end of 1975, there will be about 3,700,000 sets. From 1975 to 1990, about 2,000,000 sets will be installed. In estimating (the Arab countries have a better electrical network than the African countries south of the Sahara) by 50% the proportion of sets in need of an autonomous power source, we can estimate roughly 1 million sets by 1990. /65

— South American countries (Report of the International Colloquim on Satellites for Education, May, 1971)

Total potential: 60 - 70 million students in a few years (1975) if the audience is larger than 100 million.

Hypothesis: 80 students per television set; then one needs 1.25 million TV sets, and 1.5 million for the 100 million students mentioned before.

More modest plan: 30 million students; 400,000 TV sets.

*The Arab countries are: Algeria, Abu Dhabi-Dhabar, Arab Republic of Egypt, Jordan, Iraq, Kuwait, Lebanon, Libya, Morocco, Qatar, Saudi Arabia, Sudan, Syria, Tunisia.

Table 1 summarizes the data above.

TABLE 1. NUMBER OF SCHOOL TELEVISION SETS

	Number of television sets		Number of television sets apt to use solar power	
	1980	1990	1975-1980	1980-1990
Africa, south of the Sahara	300,000	700,000	300,000	400,000
Arab countries	4,200,000	5,600,000	2,500,000	700,000
India	500,000	800,000	500,000	300,000
South America	500,000	800,000	500,000	300,000

In our opinion, these estimates are very optimistic because they /66
suggest that these countries can find the financing necessary for these programs.

23. Water pumps for isolated villages

The number of isolated villages is estimated from statistics and forecasts on population and its distribution at 450,000 for Africa; 560,000 for India, 300,000 for Central and South America. These villages are just starting their development, and we can think that pumps will be installed in only 1% of the villages by 1980, in 4 - 5% by 1990. This will depend upon the available techniques and their cost.

24. Electricity for houses of isolated villages

See preceding remarks.

25. Isolated industries

This is a vast area and the available information is scant; however, it seems that only a few particular cases will represent the market for solar generators in this category. We will omit them in the following estimates.

26. Electricity for individual dwellings in zones with electricity

This calculation is a rough estimate in three countries: France, United Kingdom, Germany, on individual dwellings liable to use solar power for their consumption of electricity and water heating. Electrical heating is excluded at this time, considering the following argument:

— Electrical heating of an individual home consumes an average of 13 kW during 1500 hours per year with peaks of 15 kW. This means that the consumption is raised to 19,000 kWh/year for this need alone. The peak consumption is 3 times higher for heating than for all other domestic needs together: lights, hot water, household appliances. Optimistic calculations show that 150 m^2 of solar cells will be needed to fulfill, with the present techniques, the requirements in electrical heating.

On the other hand, the average consumption of an individual dwelling for its electricity needs (except heating) is 2400 Wh per day, with an average of 100 W and a peak of 5 kW. /67

The quantification of the market for the three countries: France, United Kingdom, and Germany, utilizes in part the information from Bulletins of the OCDE.

— growth rate of population from 1961 to 1971, used for the calculation of population from 1980 to 1990;

— population of these three countries in 1971 extrapolated.

The percentage of inhabitants in individual houses are given by the Planning Commission (except those for 1980 - 1990).

The percentage of individual houses situated in sunny locations (1800 hours of sun per year, i.e., an average of 8 hours every other day) was chosen approximately, based on the information from maps of the AFEDES (French Association for the Study and Development of Solar Energy), which show the curves of insolation (number of hours per year) as a function of regions and countries.

To estimate the number of individual houses liable to use solar energy for their domestic needs, we will start with the hypothesis that all individual homes built before 1975 inclusive will be equipped with classical apparatus, considering that the market for the solar generator will not be ready.

We obtain the following estimate: /68

TABLE 2.

		France	UK	Germany	Italy	Spain	Total
No. individual houses in sunny areas (in millions)	1975	2.2	1.4	1.7	2.6	2.3	
	1980	3.4	2.4	2.5	3.3	2.6	
	1990	4.1	2.8	3.2	5	4	
No. individual houses already built apt to use solar power (in millions)	1975/1980	1.2	1	0.8	0.7	0.3	4
	1980/1990	0.7	0.4	0.7	1.7	1.4	4.9
	TOTAL (1975-1990)	1.9	1.4	1.5	2.4	1.7	8.9

These estimated figures indicate that about 9 million houses in the 5 countries will be apt to use solar energy (almost 2 million for France) by 1990.

27, 28. Industrial and commercial buildings - electric power plants

We do not have estimates for these applications; probably remote.

SUPPLEMENT 3

CLIMATOLOGY OF SOLAR RADIATION*

M. PERRIN DE BRICHAMBAUT**

The National Departments of Meteorology under the supervision of the worldwide Meteorologic Organization have slowly brought about a precise determination of the climatology of solar radiation. The exploitation of satellites permits filling in the blanks in the observation network at ground level and, presently, the diagram of the annual sums, indicated on the map included, can be considered for the energy to be received from the sun by the ground, assumed to be horizontal. We will remind you that 1 kilojoule/cm^2 is the equivalent of 3 kWh/m^2 in our area, the annual values in the range of 1200 kWh/m^2 are normal. /69

However, the homogeneity of measurements at the world scale cannot be ensured with certainty because of the problems brought forth by the radiometric scales, but also because of the diversity of the instruments and of the methods of recording, and of the very frequent lack of comparison and controls of the apparatus. On a national scale, or even at the level of Western Europe, it might be possible to compare the results with an approximation of 5% at best for the daily sums of total solar radiation hitting a horizontal surface. /70

Recordings over 15 years of the length of insolation and for a few years of the total radiation allow us to trace the following maps of the solar energy hitting the ground, in terms of averages per day,

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*National Meteorology, Paris-Boulogne.

**This document is being considered for publication by AFEDES.

for the months of January and July in France and for each year. The figures given in joules per cm^2 can be converted into industrial units by the formula: $100\ j/cm^2 \simeq 0.3\ kWh/m^2$. We obtain for Trappes about 1 kWh/cm^2 per day in winter, and 6 - 10 kWh/m^2 daily in summer, with an annual average of 3.3 kWh/m^2.

A complete utilization of the data obtained to this day would allow much safer values, and would ensure their statistical analysis. In fact, these mean values alone are very insufficient for most applications, and some indication of the <u>values of the extremes</u> (minimum and maximum) of the total solar energy received daily are necessary. For instance, as far as Trappes is concerned, the following deviations can be observed: /71

DAILY SUM OF THE TOTAL SOLAR RADIATION IN TRAPPES
(joules per cm^2; daily average)

	Max.	Decile	Quartile	Median	Quartile	Decile	Min.	Avg.
Jan.	800	600	400	240	150	130	90	280
July	3000	2600	2400	2050	1500	1400	500	1970

Such tables, established for each climatic area in France, could allow the correct optimization of the operation of plane horizontal insolators, but the choice of the threshold of functioning through the problem of storage cannot even yet be approached; for this purpose, the probability of the sequence of 1 and 2 or several days putting out a power greater than the considered values would have to be statistically evaluated.

We must also study in detail the immediate or hourly values of the total solar radiation in order to determine optimally the daily time of operation of the systems for collecting solar energy.

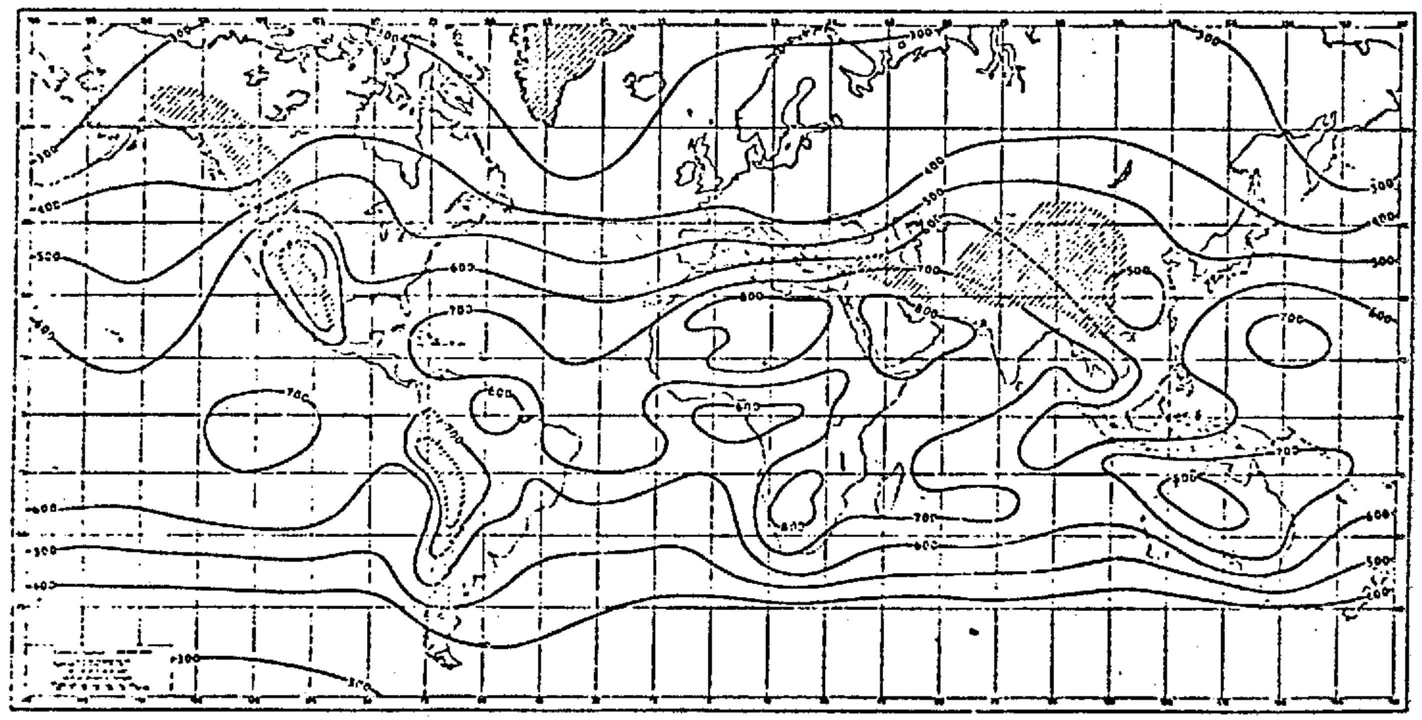
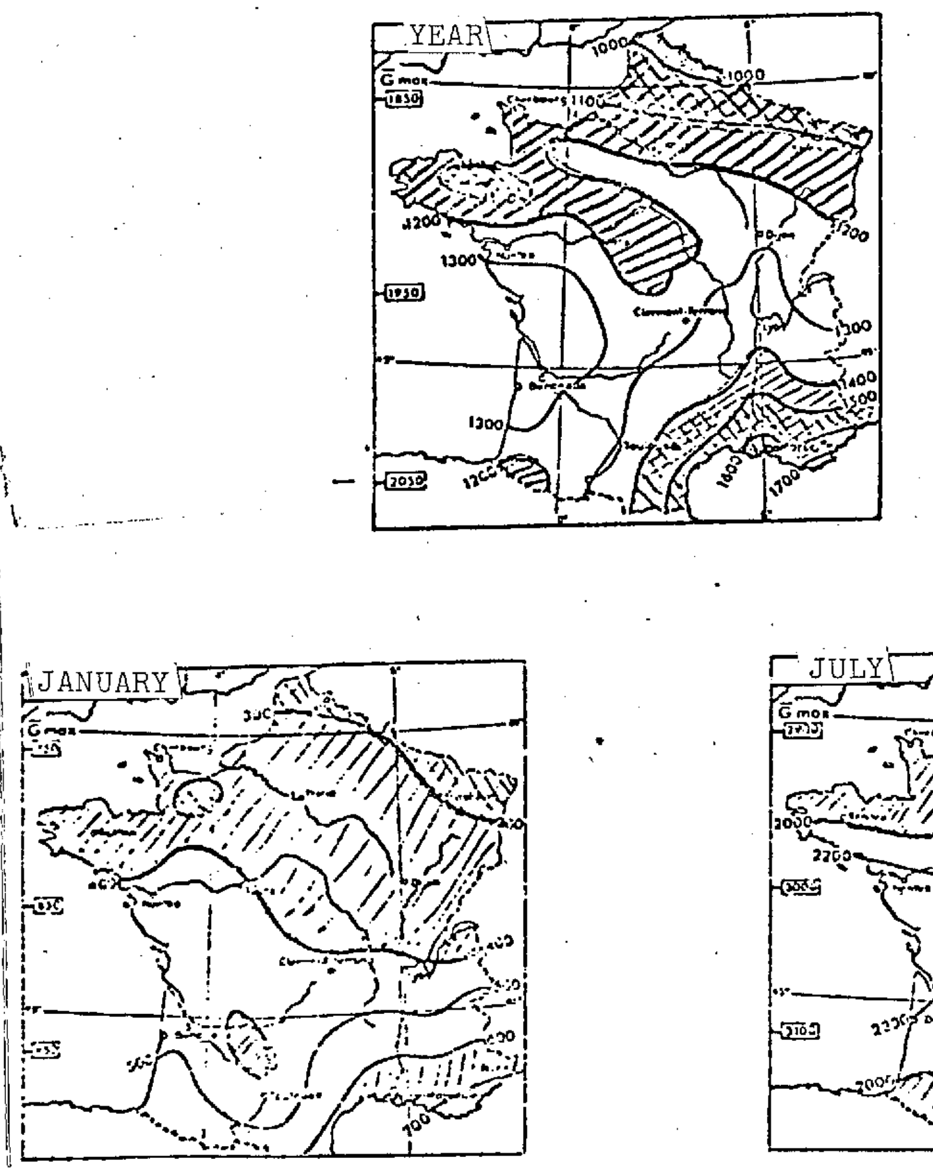


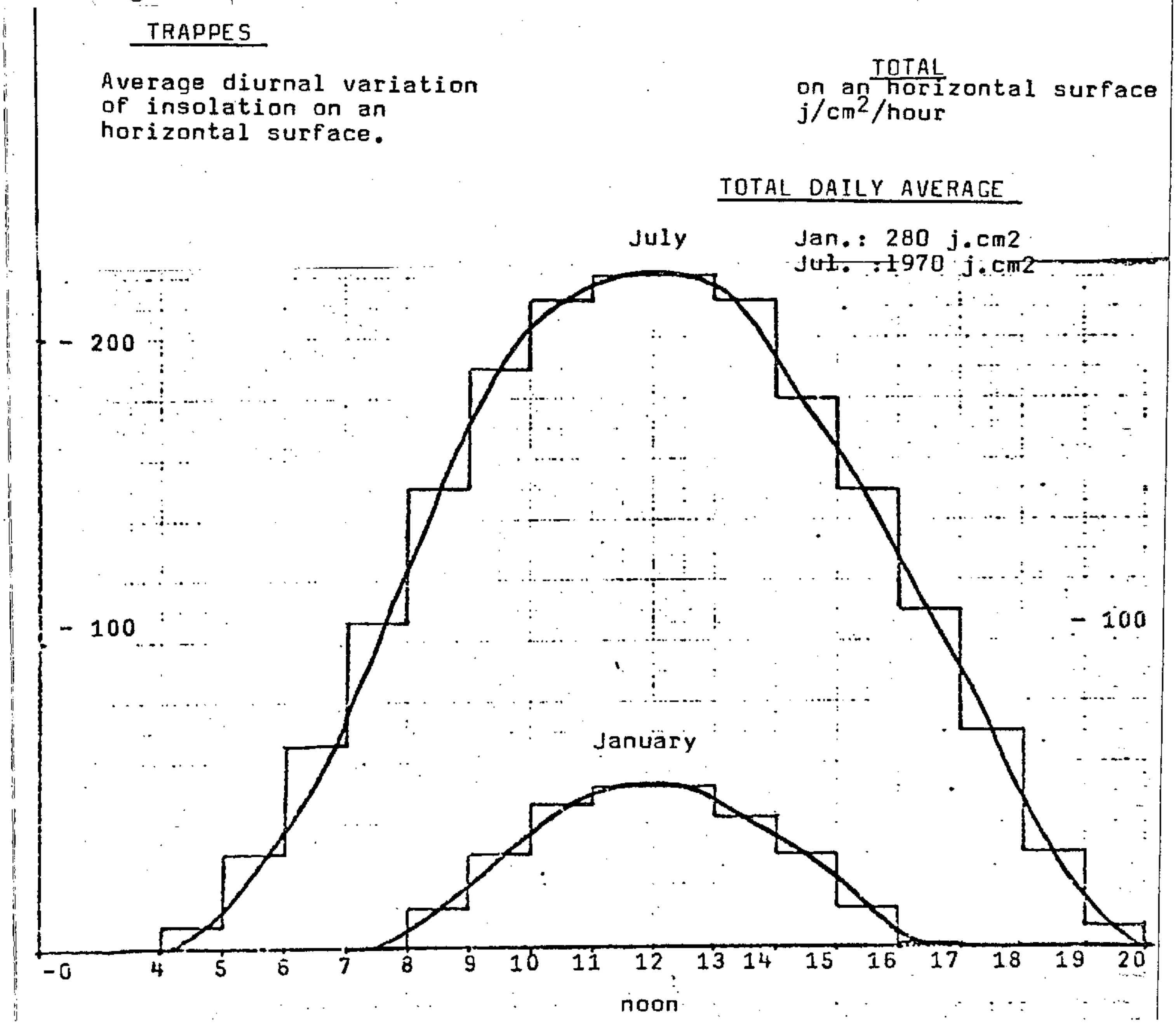
Figure 1. Annual sums of total insolation (kilojoules per cm^2 per year)
AFEDES Book No. 1, p. 94



From AFEDES Book no1

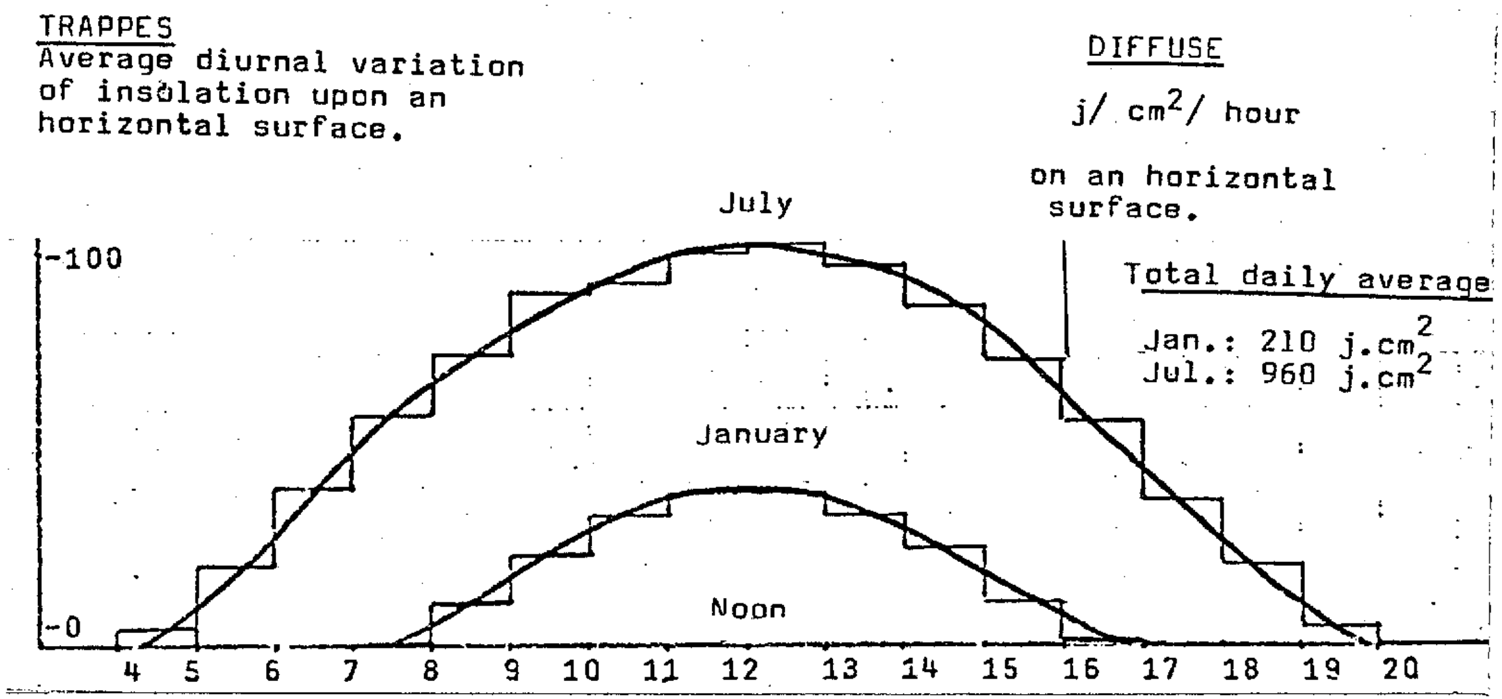
Figure 2. Monthly average (January and July) and annual average of the total daily amount of insolation at ground level
Curves in joules/cm^2/day

Figure 3



TRAPPES
Average diurnal variation of insolation on an horizontal surface.
TOTAL
on an horizontal surface
j/cm2/hour
TOTAL DAILY AVERAGE
Jan.: 280 j.cm2
Jul. :1970 j.cm2
July
January
200
100
100
-0
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
noon

Figure 4


TRAPPES
Average diurnal variation of insolation upon an horizontal surface.
DIFFUSE
j/ cm2/ hour
on an horizontal surface.
Total daily average
Jan.: 210 j.cm2
Jul.: 960 j.cm2
July
January
Noon
-100
-0
4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

For Trappes, the average curves following indicated for January and July (hours noted in real solar time) allow a better judgment of the diurnal variation of the solar radiation upon a horizontal surface.

But the horizontal position of the collectors do not always appear to be the best, the more practical or the more efficient, and it seems necessary for the engineers and architects to be able to estimate the received energy at each moment, for each season and place, by plane surfaces of whatever slope or orientation.

To obtain such estimates, we must separate the 2 components of the total radiation and define the parts due, respectively, to the diffuse radiation and to the direct solar radiation; the meteorological and astronomical parameters seen to be determined, but their incidence remains complex and difficult to evaluate for usual cloudy days.

Regular measurements of the diffuse rays are, unfortunately, rare. The estimates can be made, with a complete statistical analysis of the data for clear days only. For the usual cases of average nebulosity, only the measurements on receptor surfaces of characteristic orientation and inclination (vertical sides, N, S, E, and W, at least) can give information useful for calculation of elements concerning all the cases (e.g., roofs), or for the realization of efficient sun shades.

As a general indication, the characteristics of the diffuse /75
radiation upon a horizontal surface can be described for Trappes as being the same as the total radiation:

DAILY SUMS OF DIFFUSE SOLAR RADIATION ON A HORIZONTAL SURFACE AT AT TRAPPES (joules per cm^2 — horizontal surface)

	Max.	Decile	Quartile	Median	Quartile	Decile	Min.	Avg.
Jan.	400	300	260	200	140	110	60	210
July	1500	1200	1100	1000	800	650	300	960

Calculations for UCCLE (Belgium) allow a diagram of the annual variation of the solar energy received by vertical surfaces of various orientations on fair weather days only.

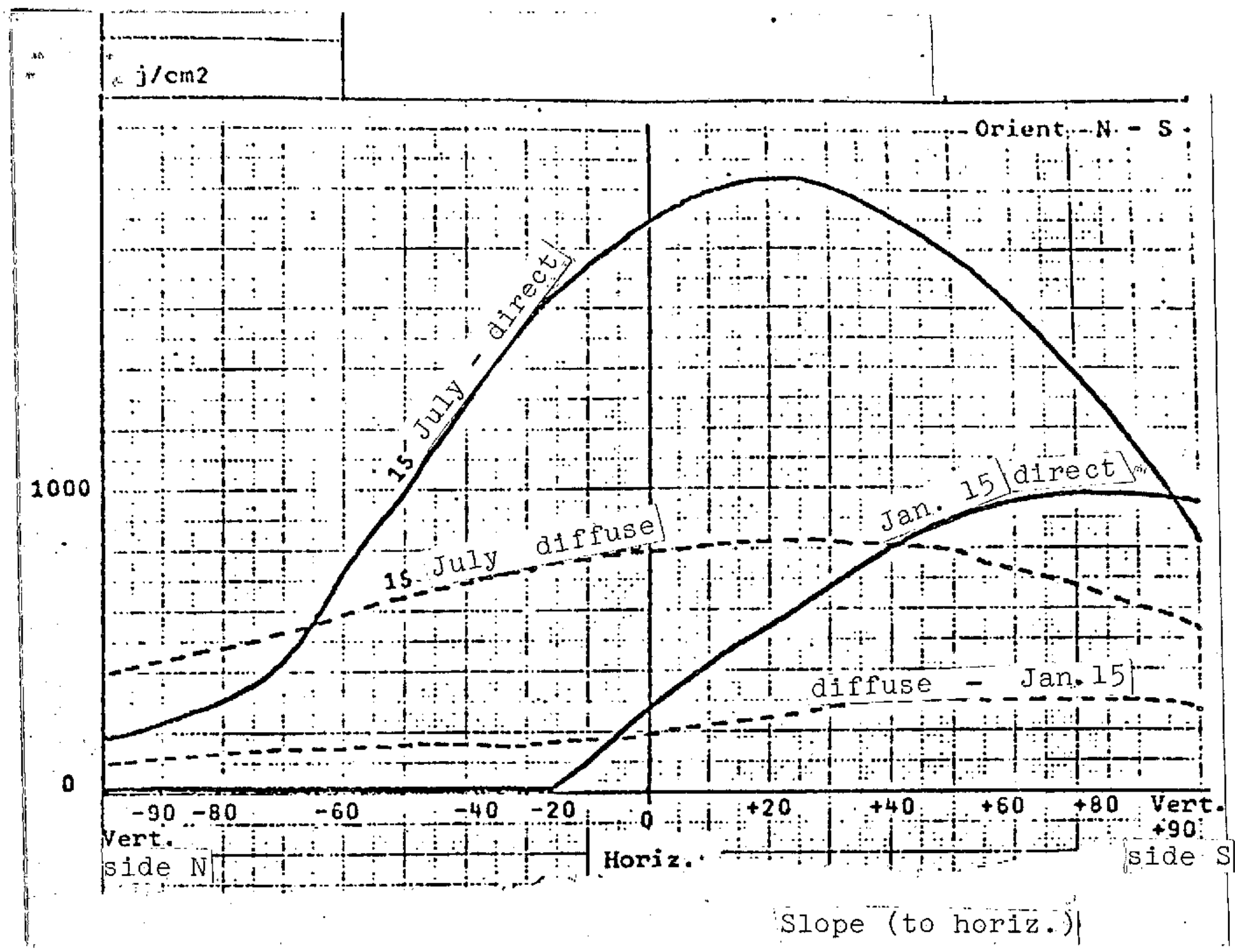


Figure 5. Daily energy — illumination for clear skies (UCCLE) according to orientation and slope of plane surfaces, due to direct and diffuse components

(Figure continued on following page)

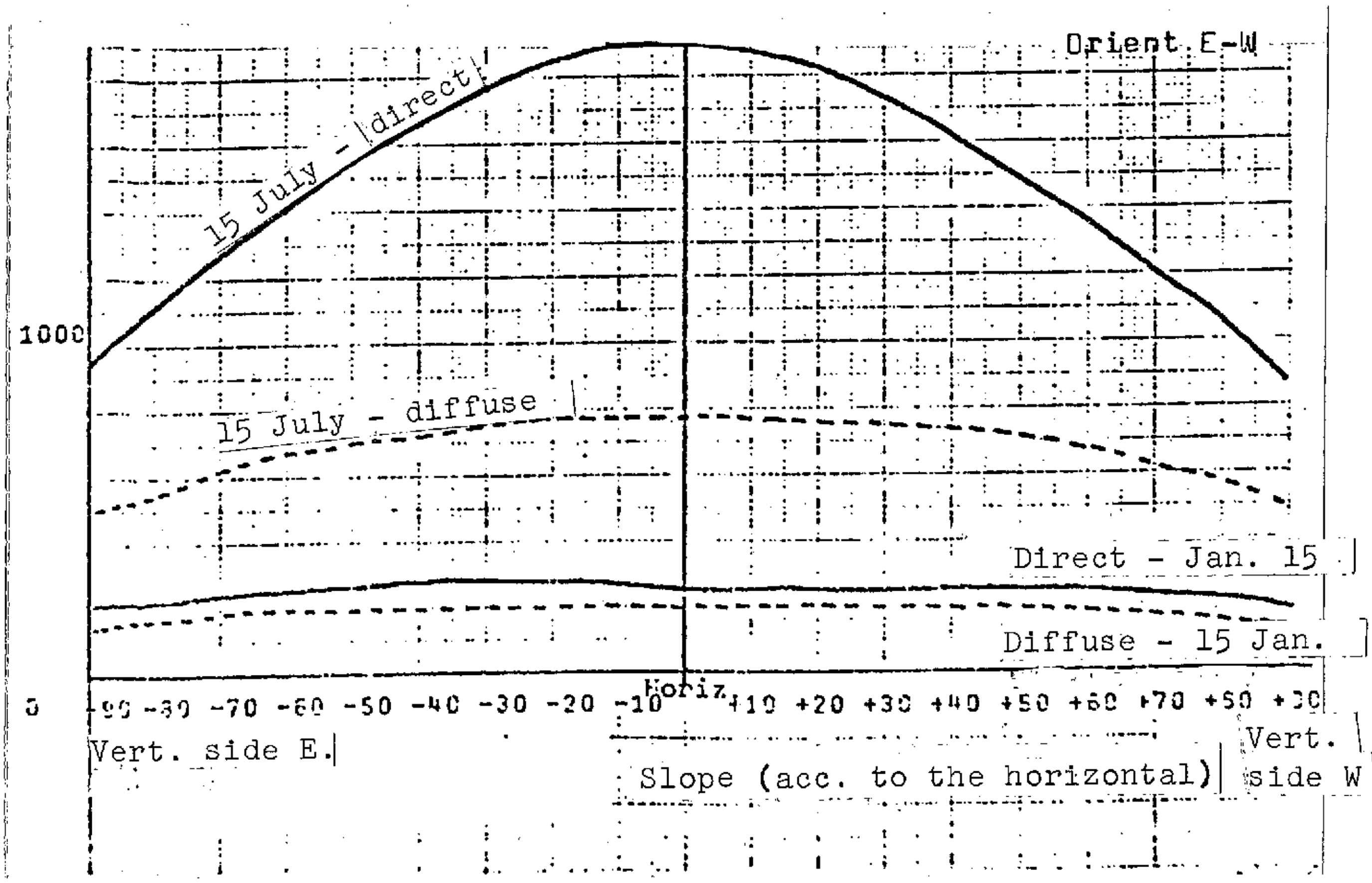
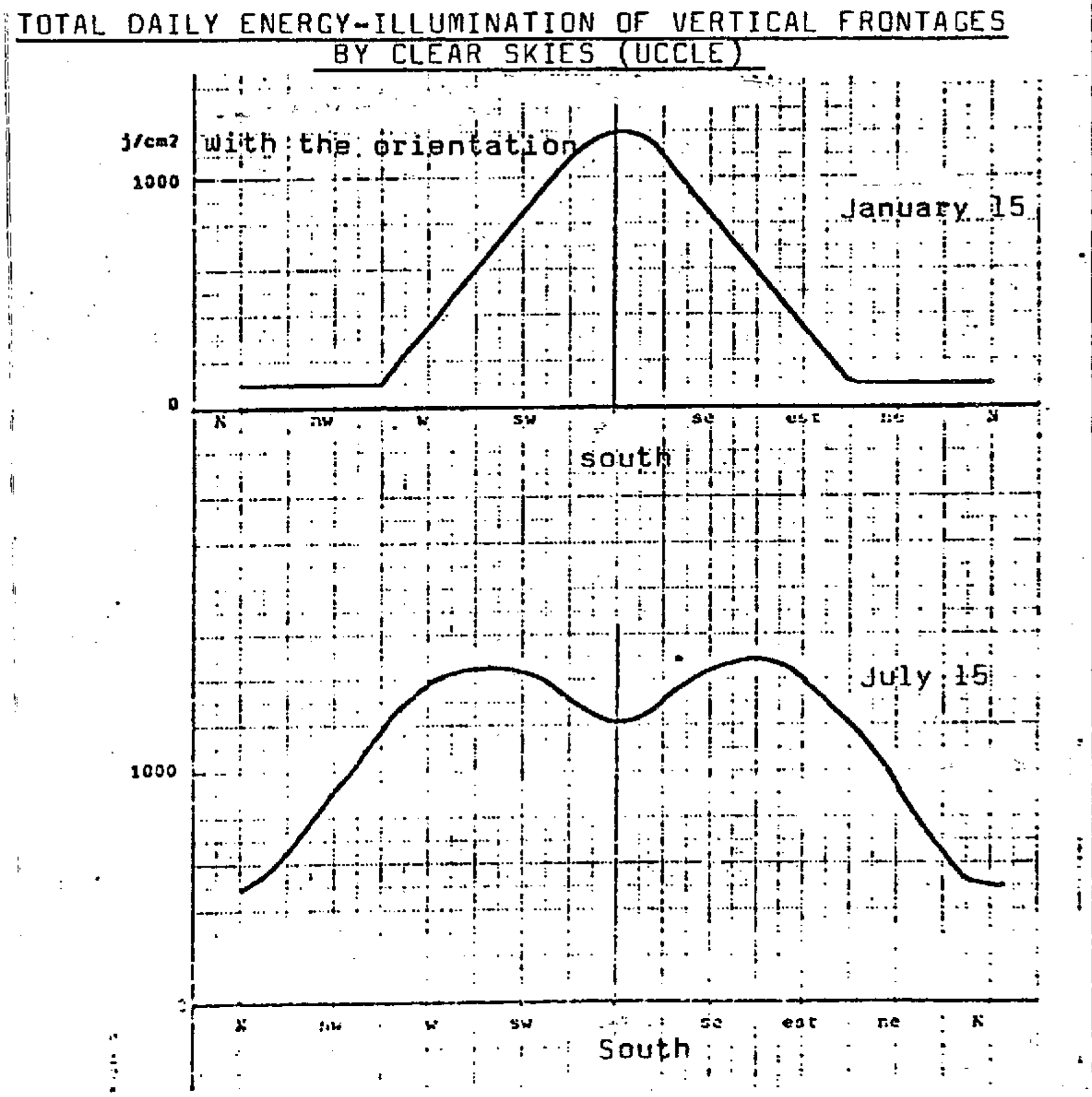


Figure 5. (continued)

Such data must be made available for the various climates and /77
for the fair weather conditions as well as for the more common meteorological conditions: they are necessary in order to estimate the maximum energetic illumination of a vertical surface in any orientation, at any time of day (for fair weather, the absolute maximum function of the reflection coefficient of the neighborhood ground corresponds to a side turned East - South - East), or to determine the slope and the optimal direction of a collecting surface designed to receive a maximum energy at a precise time of day or at a chosen season (heating water in winter for fair weather: choose the direction South, and a slope of 60°), etc.

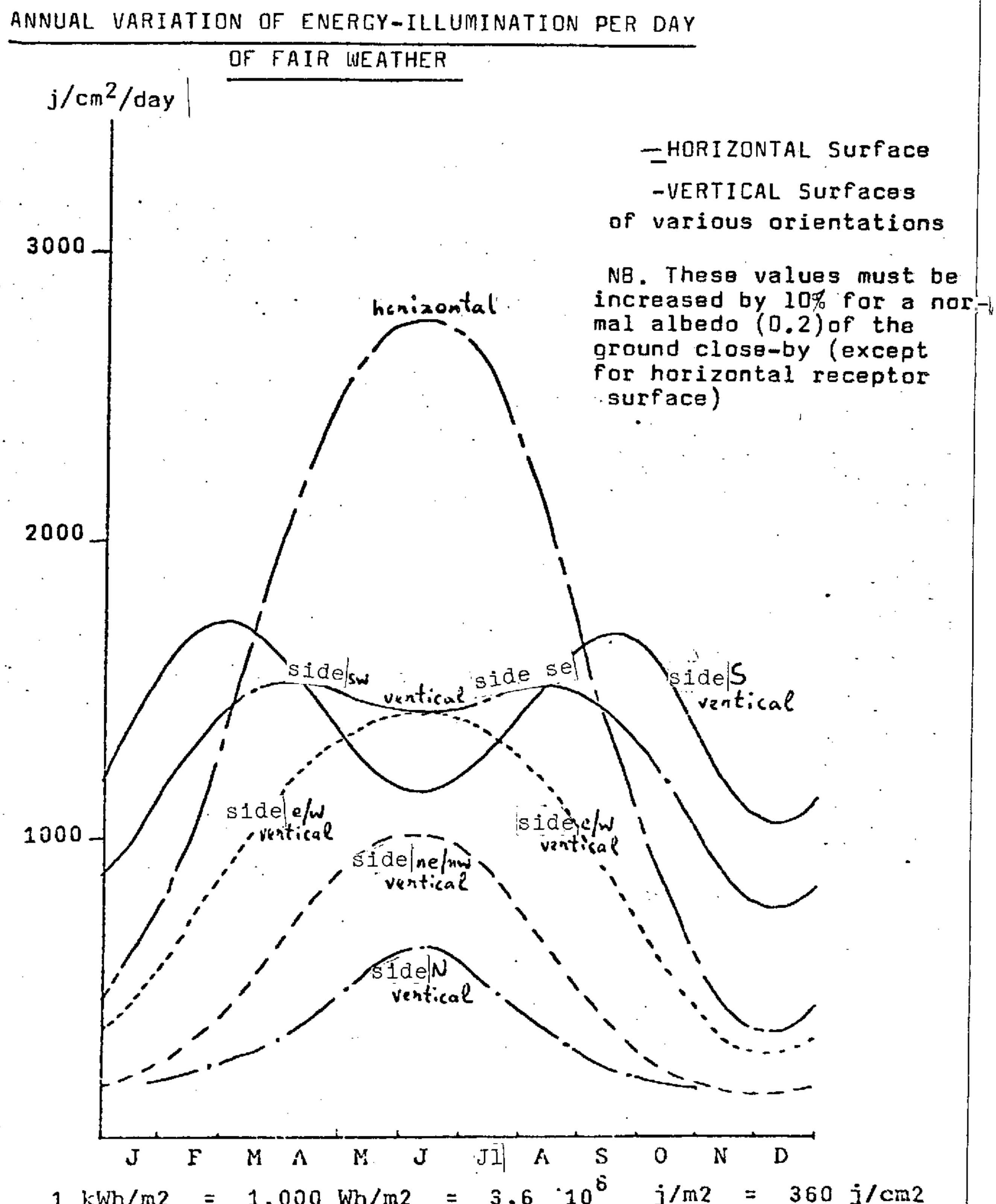
The use of parabolic collecting devices also requires knowledge of the characteristics of the daily distribution of direct solar radiation, in particular, energetic illumination and its probability

Figure 6



TOTAL DAILY ENERGY-ILLUMINATION OF VERTICAL FRONTAGES
BY CLEAR SKIES (UCCLE)
j/cm2
with the orientation
1000
January 15
0
N
nw
w
sw
se
est
N
south
July 15
1000
N
nw
w
sw
se
est
ne
N
South

Figure 6 (continued)



of occurrence. For the first point, the local climatology of the atmospheric disturbances is a necessary element, as is the altitude and the height and angle of the Sun above the horizon. The following values can be given for the power received by a receptor surface normal to the Sun's rays (watt per m^2):

Height of Sun	Clear skies	Blue skies	Greyish skies
60° (noon, July)	1100	1010	900
30°	950	750	650
15° (noon, January)	750	600	400

The complex and little known effect of the altitude requires elaborate calculations based upon precise measurements. As for the angular elevation of the Sun, it can be determined easily from the latitude of the area, the time of year and the time of day (after correction for longitude and equation of the time).

In addition, the amount of time during which the Sun is visible, without clouds, corresponds approximately to the time of insolation, measured normally by the meteorological stations. Many long series of observations exist in France, but their utilization remains insufficient for our goals: they should entail delicate statistical treatment of existing data, but also refined measurements (e.g., hourly) at least for certain regions.

The probability of sunshine can nevertheless, from today on, be estimated in most French regions by the annual variations of the ratio of insolation (ratio time of insolation to maximal duration by clear sky) characteristic for the local climate. /78

For Trappes, for example, the average length of insolation in January is 1.4 hours per day (0.9 - 2.4, according to the year) although the daylight length is approximately 8 hours. It is 7.7 in July (5 to 10 hours) for an average daylight of 15 hours. The ratio of average insolation is then 0.18 and 0.50, respectively, corresponding to the actual probabilities in January and July for the use of solar radiation by concentration.

To complete the list of fundamental needs in the matter of solar radiation climatology, one must underline the importance, in particular to the biologists, of the spectral composition of solar radiation, which varies with the elevation of the Sun, the atmospheric disturbances and the humidity: the effects of these various parameters are well known, and can be calculated at least for direct radiation. They can also be evaluated, but only for fair weather, for the diffuse and total radiation. Conversely, for average cloudy days no valid estimate can be made, even less so since the type and distribution of the clouds and the nature of the ground surface, as well as the vegetative cover, very strongly modify it. Here, also, precise measurements must be performed, which are interesting and valid only in their relationship to the general solar climate of the area studied and at the time of measurement only.

These few comments and examples show the importance of the various problems brought forth by knowledge of solar radiation climatology, with planned utilization. So if many elements are still lacking in France to fulfill all the expressed needs, a better definition of the essential characteristics of solar radiation at ground level, with respect to its utilization, could be obtained from statistical detailed analysis of a series of already existing data.

It is this basic work of synthesis, based upon various useful suggestions presented at the congress, that France must undertake, preferably in connection with particularly competent neighbor countries (Belgium, Switzerland), or with directly interested countries (Mediterranean countries, tropical Africa).